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MODEL STUDY OF EXPLOSION-GENERATED SEISMIC WAVES

Carl Kisslinger
SAINT LOUIS UNIVERSITY
INSTITUTE OF TECHNOLOGY
St. Louis, Missouri

Contract No. AF 19(628)-1689

Final Report

Period covered: 1 October 1962 - 1 October 1965

October 1, 1965

Prepared for

Air Force Cambridge Research Laboratories
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

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PROJECT VELA-UNIFORM

ARPA Order No. 292-62
Project Code No. 8652, Task 2

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Abstract

The generation of seismic waves by an explosive source in homogeneous media was investigated by two-dimensional models. The size of the effective source for compressional waves agrees well with the outer limits of the zone of circumferential cracking in a brittle medium. Prominent shear waves appear only when the source produces long radial cracks, is located near the free surface of the model, or the source is elongated. The radiation of both types of body waves is strongly modified when the source is near the surface.

The P-wave spectrum can be modified by surrounding the shot with a different material. A cavity, filled with air or a solid substance, affects the signal through both its geometric configuration and the properties of the material in the cavity.

The evidence from Rayleigh waves indicates that the effect of an explosion changes from a vertically applied source pulse to a buried center of compression when the source depth exceeds the radius of the zone of non-elastic behavior.

When the medium is statically stressed before the shot, the body waves are modified. For relatively small strains in Plexiglas, a definite, but small, anisotropy is produced by the static strain. The presence of the static strain guides the release of energy from the explosion. Complete rupture of the sheet was produced by explosions when the stress was well below the static tensile strength. Small but distinct S-waves were produced in prestressed sheets, but could not be detected in the same material without loading.

A low velocity wedge modifies wave propagation by creating a shadow zone. Diffractions into this shadow zone from the wedge tip were observed.

CHAPTER I

Introduction

The purpose of this research was to develop techniques by which the seismic effects of explosions in solid media could be studied in the laboratory and to apply these techniques to several problems of concern in the detection and identification of underground nuclear explosions. Well-established principles of two dimensional seismic modeling were employed. Instrumentation for measuring the radial and tangential components of the extensional vibrations of the model resulting from the detonation of a suitable laboratory explosive was fabricated.

Several aspects of the generation of both body and surface seismic waves were investigated. Although definite conclusions about several of these problems have been drawn, conclusions which are in at least general agreement with the results of theory, it must be emphasized that all results of model studies should be subjected to full-scale testing. Indeed, one of the values of model studies is the insight they provide as an aid in the design of full-scale experiments.

In the present work, measurements of the explosion-induced stress waves were made in the close-in elastic region. In addition, these experiments have afforded the

opportunity of directly observing the zone of failure produced in the solid material by the explosion. An attempt has been made to relate the failure mechanism to the properties of the seismic signal.

Papers and Publications Based on the Research.

The scope of the work accomplished is indicated by the papers presented at scientific meetings and published in scientific journals that were based on the research.

1) C. Kisslinger and I. N. Gupta, Studies of Explosion-Generated Dilatational Waves in Two-Dimensional Models, Jour. Geophys. Res., 68: 5197-5206, 1963. Presented to 44th Annual Meeting, American Geophysical Union, April, 1963.

2) C. Kisslinger and I. N. Gupta, Two-Dimensional Model Studies of Explosion-Generated Seismic Waves. Presented to Thirteenth General Assembly, International Union of Geodesy and Geophysics, Berkeley, California, August, 1963.

3) I. N. Gupta and C. Kisslinger, Model Study of Explosion-Generated Rayleigh Waves in a Half-Space, Bull. Seis. Soc. Amer. 54: 475-484, 1964.

4) I. N. Gupta and C. Kisslinger, Model Study of Seismic Waves from Explosions in Rectangular Cavities, Bull. Seis. Soc. Amer., 54: 1105-1113, 1964.

5) C. Kisslinger, Small Scale Studies of Explosive Seismic Sources. Presented to VESIAC Special Study

Conference, La Jolla, California, 22-24 March, 1965.

6) D. S. Bahjat and C. Kisslinger: Model Study of Radiation from an Explosion in a Circular Disk. Presented to 46th Annual Meeting, American Geophysical Union, April, 1965. Abstract in Trans. Amer. Geophys. Union, 46: 145, 1965.

7) I. N. Gupta and C. Kisslinger: Radiation of Body Waves from a Near-Surface Source. Presented to Annual Meeting, Seismological Society of America, April, 1965.

8) W. H. Kim and C. Kisslinger: Model Study of Seismic Effects of Explosions in a Pre-stressed Medium. Presented to Annual Meeting, Eastern Section, Seismological Society of America, October, 1965.

Personnel.

The following members of the Department of Geophysics and Geophysical Engineering were engaged in the research program at various stages:

Carl Kisslinger, professor, was principal investigator.

Indra N. Gupta, graduate research assistant, completed his Ph.D. degree in June, 1964. His dissertation was based on the investigation of Rayleigh waves carried out under this program.

Won H. Kim and Dhari Bahjat, graduate research assistants, are completing the requirements for the Ph. D. degree.

John T. Maschmeyer, an undergraduate in the Institute

of Technology, worked on research related to the project under the auspices of the National Science Foundation Undergraduate Research Participation program in the summer of 1963.

Experimental Procedure and Instrumentation.

The experimental technique has been described in detail in Kisslinger and Gupta (1963) and Gupta and Kisslinger (1964a), and only a summary will be presented here. A schematic of the laboratory set-up is seen in Figure 1-1. A small charge, approximately 10 milligrams, of silver acetylide, is detonated at the selected shot point, either in a close fitting hole drilled in the model sheet, or in contact with the free edge of the model. The flash of light accompanying the explosion is detected by a photocell, and the resulting pulse triggers the sweeps of the oscilloscopes. The resulting elastic waves are detected and the display on the oscilloscope photographed. The types of detectors used will be discussed below.

An explosive source has one disadvantage in comparison with pulsed transducer sources more commonly used in model studies: there is only one opportunity to record the signal. For this reason, four channels of recording have been employed in most of the experiments. In addition, in many experiments it was desirable to use a single recording set-up and record several shots with it. This implies the use of several shot points in the same model

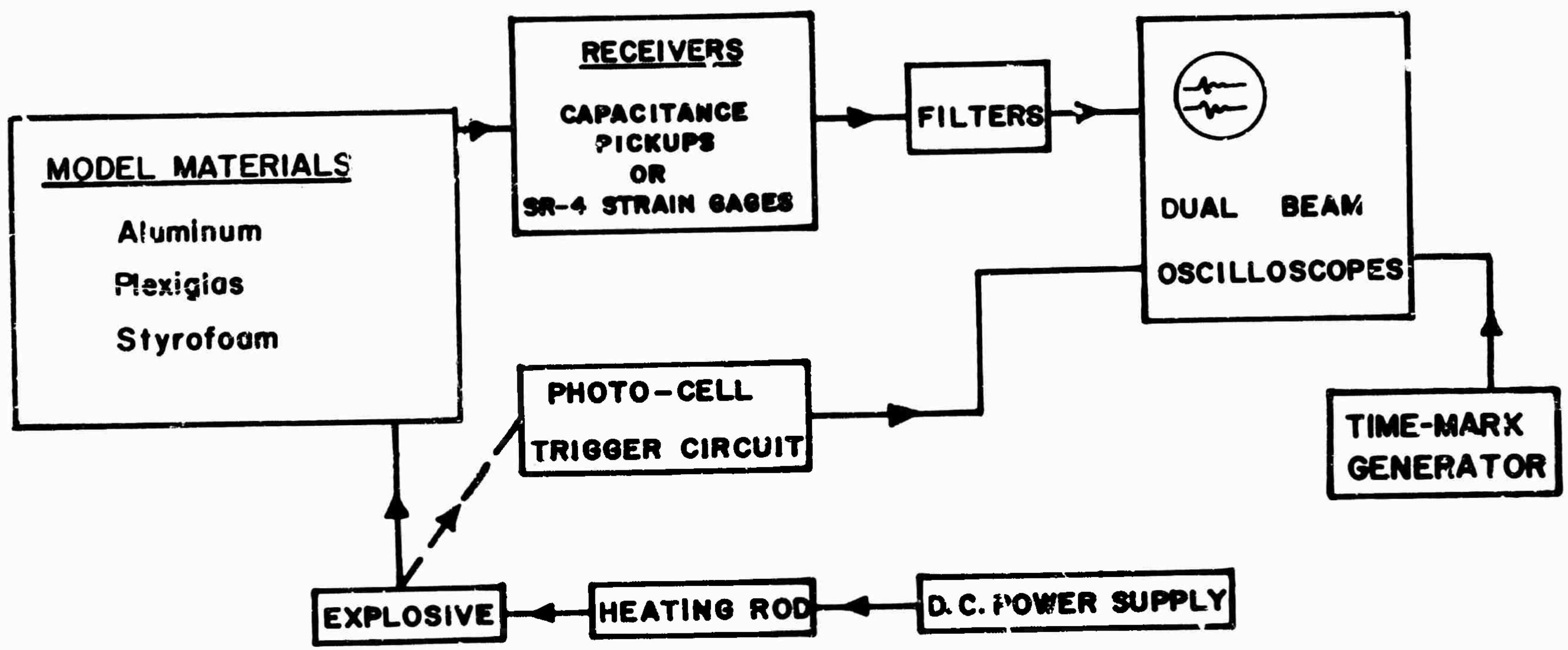


FIG.I-I SCHEMATIC DIAGRAM OF THE EXPERIMENT SET-UP

sheet. Because these shot holes become scattering centers, in all such experiments the shots farthest from the detectors were fired first, and then the closer ones. In this way the fractured regions around each shot were not between the subsequent shots and the detectors. Since the wavelengths involved were considerably longer than the largest dimensions of the shot holes, even after firing (the order of 10 centimeters compared to one centimeter or less), the effect of scattering by multiple shot holes is not considered to be important.

The frame which was constructed to hold the models, with the arrangement to allow stretching of the models in the experiments on the effects of prestressing, is seen in Figure 1-2. Tensile loads up to 20,000 pounds can be applied with this device.

The Explosive Material. The silver acetylide ($Ag_2C_2 \cdot AgNO_3$) is prepared by bubbling acetylene gas (C_2H_2) through a neutral aqueous solution of silver nitrate. The charges are formed in a special die from the resulting precipitate while it is still moist and putty-like. The material is compressed to density of about 2 gm/cm^3. The normal charges are 1.25 mm in diameter, and are cut to various lengths, depending on the thickness of the sheet of material. For some experiments, the explosive was pressed while still moist into the shot hole. The advantages of this material as a laboratory explosive

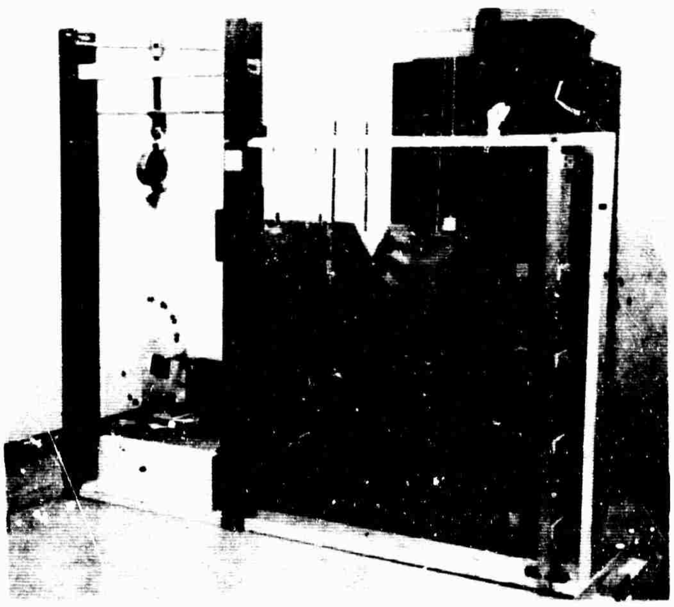


FIG.1-2 LOADING AND FIXTURE FRAME

are in its ease of preparation, ease of casting into the desired form, and ease of detonation.

The Model Materials. Aluminum, Plexiglas, and Styrofoam were selected as model materials because they are readily available in large, thin sheets, they have very different elastic constants and densities, and because they fail under explosive loading in different ways. The emphasis in this research was on the mechanism of wave generation rather than on propagation. It is well known that the properties of the shot point medium significantly affect the seismic signal, and so it was desirable to have media with distinctly different properties available.

Aluminum is ductile, and at the shock pressures encountered in these experiments, fails by plastic flow, with only minor cracking. Plexiglas is brittle, and its failure exhibits the typical features of explosions in rocks. Styrofoam is easily crushable, and the explosive pressure produces a large circular hole.

The Instrumentation. Three types of detectors were used at various times: ceramic transducers (barium titanate and lead zirconate), capacitance transducers, and SR-4 strain gages. In the capacitance pickups, one plate of the capacitor is the probe and the other is the flat side of a hole in the specimen in which the probe is inserted. In the case of non-conducting model materials, a piece of metal foil is fixed to the hole, while for metal sheets, the model itself forms the other plate. A potential dif-

ference ranging from 150 volts to 500 volts is applied across the capacitor. The capacitor is coupled through a cathode follower, through 60 cps and 120 cps rejection filters to the input of the oscilloscope. The overall frequency response of the detecting system is from d.c. to about 250 kcps. The capacitance pickups used are not calibrated to give absolute measures of displacement, but were adjusted to equal sensitivity in a given set of observations.

For investigations in a prestressed medium, SR-4 dynamic strain gages were employed, in addition to the capacitance probes, to yield desired quantitative measures. These made possible the calculation of seismic energy in the compressional elastic waves.

The oscilloscopes used are two dual-beam Tektronix models, 502 and 502A, with frequency response from d.c. to an upper limit of 0.1 - 1 mcps, depending on sensitivity. Because the precise place on the pulse waveform from the photocell at which the sweep is triggered depends on the trigger level setting, a variable error (5-15 μsec) can be introduced into travel times read on the records. For this reason all velocity determinations were based on transit-times between two probes, rather than time from the source.

CHAPTER II

Generation of Body and Surface Seismic Waves

Compressional Waves in the Infinite Medium.

In order to gain insight into the basic principles underlying the experimental method to be employed, the first problem investigated was that of the generation of the primary compressional wave by an explosion in an infinite sheet. This problem bears the same relation to two-dimensional seismology that the point source in an infinite homogeneous medium bears to three-dimensional seismology (Sharpe, 1942). Strictly speaking, the analogous problem in three dimensions is the infinite line source of compressional waves or infinitely long cylindrical cavity of small diameter loaded with uniform normal stress on its walls.

The theory was developed in Kisslinger and Gupta (1963). The integral solutions were evaluated numerically and curves showing peak displacement as a function of distance, the travel time curve of the peak displacement, the waveform at large distances for impulsive, step-function, and exponentially decaying pressure time functions on the cavity boundary, and the effect of Poisson's ratio on the waveform were plotted.

The compressional waves generated by explosions in the three media were compared with these theoretical results.

The plate wave and shear wave velocities in the three media were determined to be:

Aluminum: $V_p = 5.4$ km/sec; $\beta = 3.1$ km/sec

Plexiglas: $V_p = 2.3$ km/sec; $\beta = 1.35$ km/sec

Styrofoam: $V_p = 0.9$ km/sec; β not measured, estimated as 0.5 km/sec.

The amplitudes of compressional waves in Plexiglas are about fi times those produced by the same yield in aluminum. Waves in Styrofoam are about 20 times as big as those in aluminum.

The spectrum of the compressional arrival in aluminum is flat from 1 kcps to 50 kcps, and falls off slowly (about 2 db/octave) out to at least 100 kcps. In Plexiglas, the spectrum is almost flat from 7 to 30 kcps, with a peak near 26 kcps. The spectrum in Styrofoam is more sharply peaked near 8-9 kcps. The trends of both the amplitudes and the frequencies are in agreement with the theoretical results when reasonable assumptions about the input pressure pulse shape are made.

Because the cavity size affects the frequency content of the compressional signal, it is possible to estimate the size of the equivalent radiator from the data. In Styrofoa ne large circular hole is taken as the size of the source. In Plexiglas the source region is marked by both circumferential and radial cracks. Much better agreement is obtained with the theoretical predictions if the radius of the zone of circumferential cracks is used a

the cavity radius than when the greatest extent of the radial cracks is used. This is also in agreement with the general observation that the explosion generated P waves with equal amplitudes in all directions. The generator should be circularly symmetric, as the zone of circumferential cracks is.

Shear Waves in the Infinite Medium.

The generation of shear waves by an explosion in solid media has often been observed, but a complete theory has not been developed. Alternate mechanisms that are available are departures from symmetry of the source due to departures from homogeneity of the medium around the shot, and the release by the explosion of non-hydrostatic strain pre-existing in the medium (Kisslinger Mateker, and McEvilly, 1961, Press and Archambeau, 1962, Toksöz, Harkrider, and Ben-Menahem, 1965). Both of these mechanisms were investigated in this research program. Only the results for the asymmetric source will be discussed here. The work on the pre-stressed medium will be reviewed in the next chapter.

Shear waves propagating directly from the source were either very weak or not detectable (Styrofoam) in the experiments described in the previous section. Apparently all of the model materials were sufficiently homogeneous and isotropic that the explosions were essentially symmetric. In order to produce prominent shear waves, rectangular holes were used as shot points. The experiments are described in full in Gupta and Kisslinger (1964b).

The rectangular shot points were intended to simulate the elongated radial cracks which are the result of underground explosions, especially when detonated in brittle media. Since the charges were detonated at the center of the cavity, the system approximated a bilateral crack of finite length.

The theoretical radiation patterns of P and S waves for a bilateral crack in an infinite medium were derived by Knopoff and Gilbert (1960). In addition Heelan's result (1953) for radiation from a cylinder yields the same radiation pattern for both types of body waves.

To obtain the radiation patterns in aluminum, the experimental set-up shown at the bottom of Figure 2-1 was used. The detectors were fixed along a line and cavities oriented parallel to this line, perpendicular to it, and at 45° to it were employed. Three detectors of tangential motion were employed to permit certain identification of the propagating shear wave, and a single radial detector was used. The variation of peak amplitude of the P and S wave is also shown on the figure. The change in polarity of the S wave with tilt of the shot cavity was definite. After correcting for attenuation with distance, the radiation patterns at the top of the figure were obtained. The shape of these patterns is in excellent agreement with the theory, but the P waves were much bigger relative to the S waves than predicted.

The experiments in Plexiglas were complicated by the

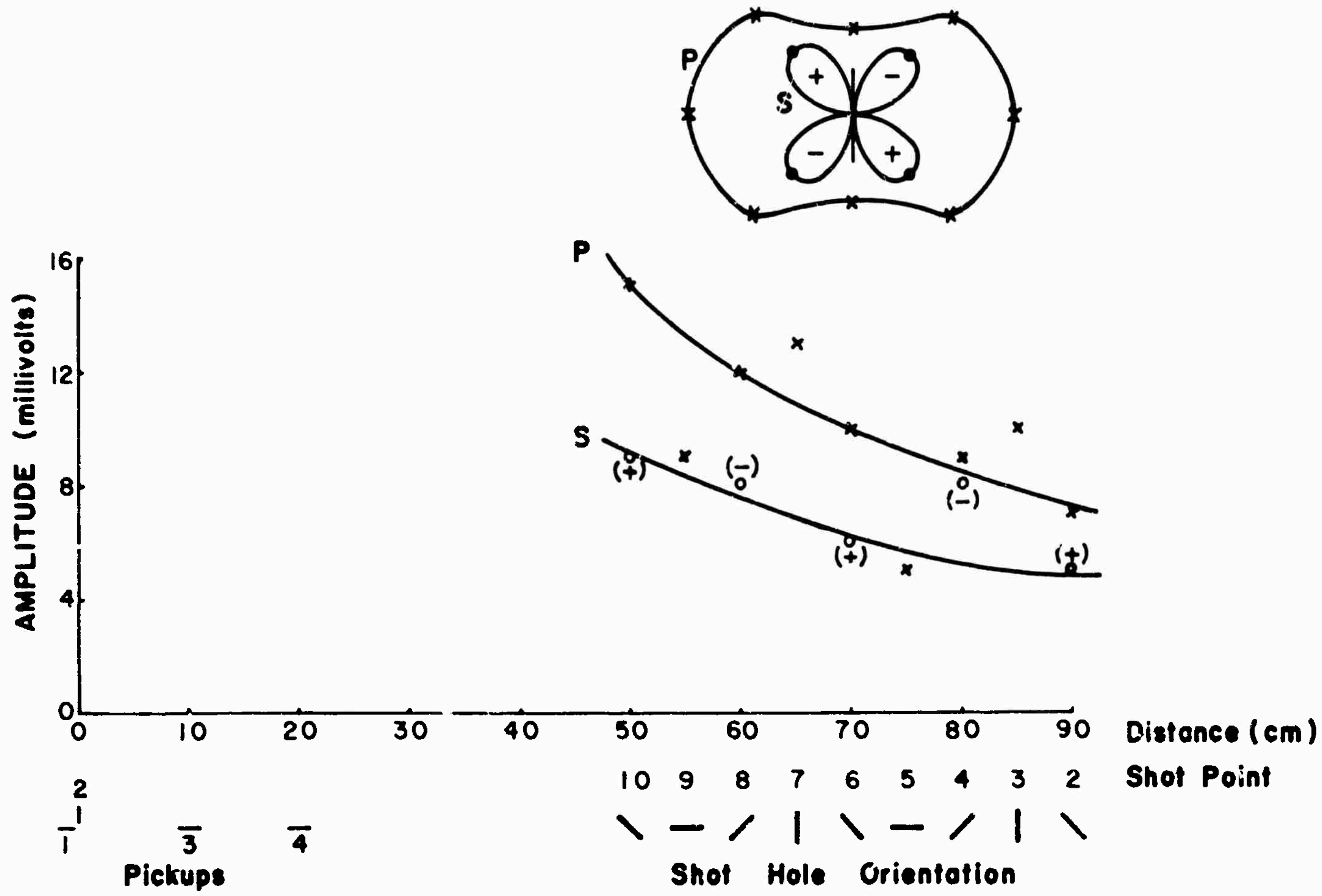


Fig. 2-1 Experimental Arrangement and Body Wave Radiation Patterns for Rectangular Sources in Aluminum

prominent cracks formed at the corners of the cavities. This behavior was expected for this material, but modified the radiation of seismic energy. The patterns were generally similar to those in aluminum, and the importance of the shape and orientation of the shot hole in determining the amplitude and sense of first motion of the S wave was established beyond doubt. Essentially the same pattern was found when a circular (normal) charge was fired in the center of the rectangle and when the rectangle was packed full of explosive material. The P waves were more nearly uniform in amplitude and the S waves were smaller for the case in which the cavity was filled with the explosive, indicating this resulted in a more nearly symmetric source.

The Effect of the Surface on Radiation of Body Waves.

Although the results for an infinite medium give important insight into the wave generating mechanism, actual seismic sources are located more or less near a free surface, and this surface drastically modifies the radiation of seismic energy (Burridge, Lapwood, and Knopoff, 1964). The direct examination of this effect in the field is difficult because it requires the emplacement of a number of detectors under the shot. An approximation of the problem was achieved in earlier field investigations with small dynamite charges by firing near the top of a vertical boundary in a limestone quarry and recording on the horizontal rock face. P waves were radiated with minimum amplitude in the direction normal to the face and maxima were found

at 45° to the face. S waves showed a node at right angles to the face, with reversed polarity on either side, and maxima at 45°. It is not known if the largest amplitudes were actually transmitted at 45° or some other angle because of the limited number of instruments.

This problem could be investigated readily by the model technique. The results are described in detail in Semi-Annual Technical Report Number 4 under this contract. Plexiglas was selected as the model material because it exhibits brittle fracture, similar to the rock in the field experiments. Four capacitance probes were used to measure P and S waves at points 35 cm from the shot along a 90° arc of the circle with the shot point at or near the center. The shot points were on the surface and at depths of 1 mm, 2mm, and 4mm from the surface. The shots in the interior of the sheet all produced craters. A final experiment used a triangular wedge cut in the edge of the sheet, packed with the explosive, as a source.

The laboratory records do exhibit features similar to the field records. The onset of the S wave is clearer on the laboratory records, but the field records do indicate S motion with initial motion in the direction of that in the model experiments.

The model data were compared with theoretical results for a surface line source. By combining the predicted patterns for vertical and horizontal stress at the source, radiation patterns similar to those observed could be

derived. In particular the drastic variations of the S wave amplitude in the neighborhood of the critical angle for S to P conversion on reflection were observed.

The surface amplitude of the P wave was found to be large, and clearly a distinct event from the waves penetrating the interior. It is a head wave associated with the free boundary. The attenuation of this wave with distance has not been compared with that of the regular P wave, and this should be done in future experiments.

The conclusion of this work is that a cratering shot can be represented by a combination of horizontal and vertical force applied at the surface and the radiation is explained by established theories for surface sources.

<u>Radiation from a Circular Inhomogeneity -- Decoupling</u>.

Decoupling remains one of the thorny problems of underground nuclear test detection. As detection capability has increased through improved instrumentation, the use of arrays, and more effective data processing, the question of how effectively a test may be concealed by detonating it in a cavity, or in a cavity filled with an energy-absorbing material, has remained unanswered and of ever greater importance.

Two-dimensional models are not an appropriate device for studying decoupling because the explosion is free to vent in the direction normal to the sheet, and a true tightly coupled shot is never achieved. The absolute

reduction in energy in the seismic signal produced by a cavity around the shot is difficult to assess. However, the way in which the spectrum of the P wave is affected by the introduction of a cavity, filled with air or some new material, can be measured. The emphasis in this research has been on an investigation of this aspect of the problem.

The medium in which an explosion is detonated affects the radiated seismic energy in two ways: its response to the shock wave that travels through it, determined by its physical properties; and by its geometric configuration. Most of the work on the explosive seismic source has treated the source medium as infinite in extent, and has evaluated only the first of these effects. The geometric factor has not received much attention except for the influence of the size of the cavity in decoupling studies. In this work, the spectrum of the compressional waves is related to the size of the circular region around the shot and the contrast in properties between the inhomogeneity and the surrounding medium.

In one series of experiments charges were fired in the center of circular holes with diameters from 1.3 mm ("tightly coupled") to 6.4 mm in aluminum and Plexiglas, and up to about 4 cm in Styrofoam. In the second series, circular discs of one of the materials were cemented into holes cut in a large sheet of another material, and shots were fired at the center of the discs. The discs were varied in size from very small ones that were destroyed

by the explosion to ones with diameters equal to about one-fourth the compressional wavelength in the disc material. The radial component of motion was recorded at points in the "infinite medium." The results of the decoupling experiments are reported in Semi-Annual Technical Report Number 3, and the disc experiments are reported in Semi-Annual Technical Report Number 5 under this contract.

An approximate theory of the geometric effect was developed by considering the disc as a circular radiator with a point source of simple harmonic compressional waves at its center, and computing the amplitude in the infinite medium as a function of the frequency of the source, assuming a constant amplitude at the source. The actual input spectrum is, of course, not flat, but is that produced by an explosion in the disc material. The spectrum of the recorded wave was divided by the known spectrum of the input waveform in an attempt to recover the geometric effect alone.

Air-filled Cavities. The variation of peak amplitude with cavity diameter from two series of decoupling experiments in aluminum and two series in Plexiglas are shown in Figure 2-2. In both materials the unexpected result that the amplitudes reach a minimum, and then increase is observed. Further, the cavity diameter at which the minimum is found is reproduced in the two series in each material, even though the curves are not otherwise reproduced in detail. The minimum is found for a larger radius in Plexi-

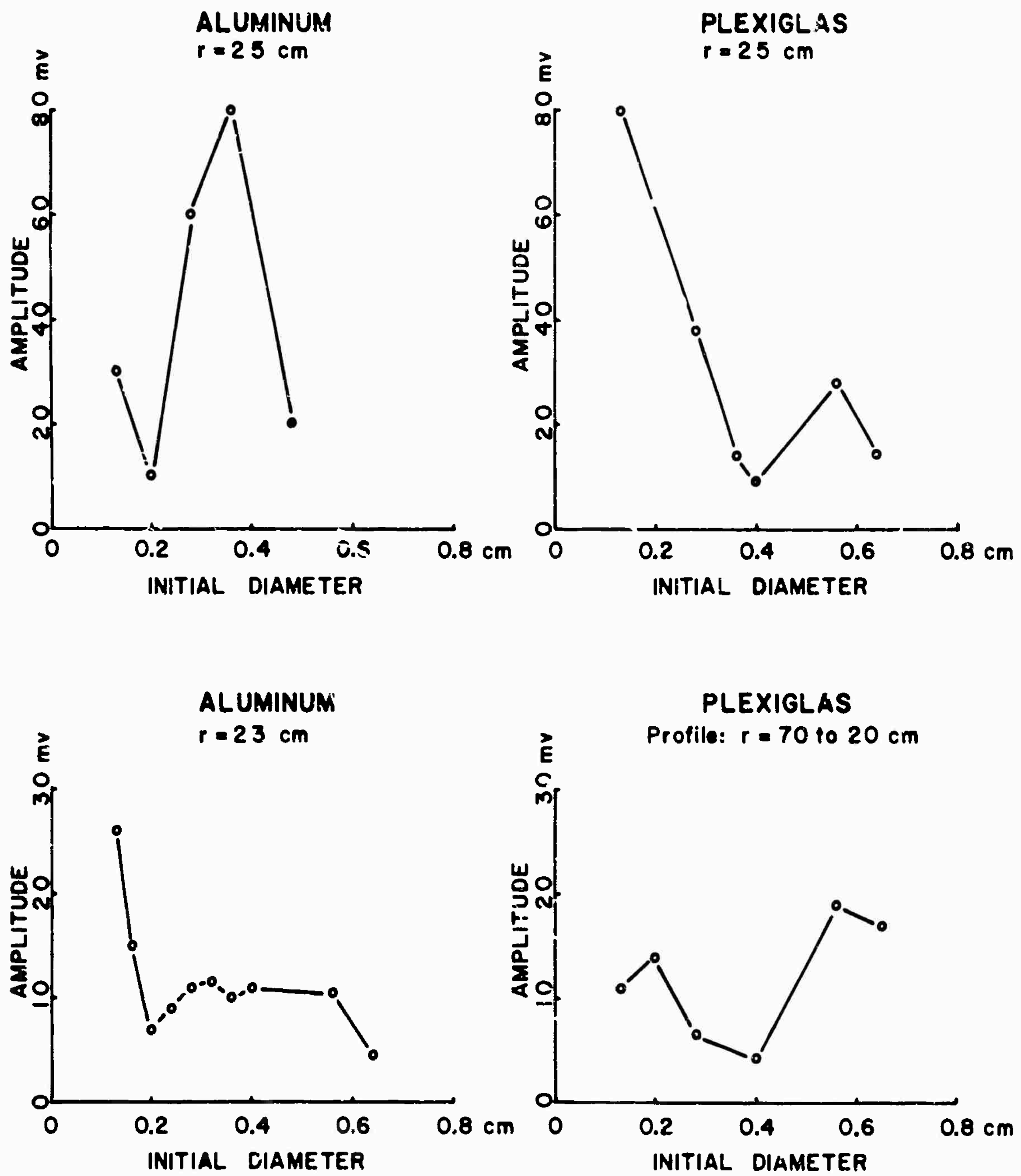


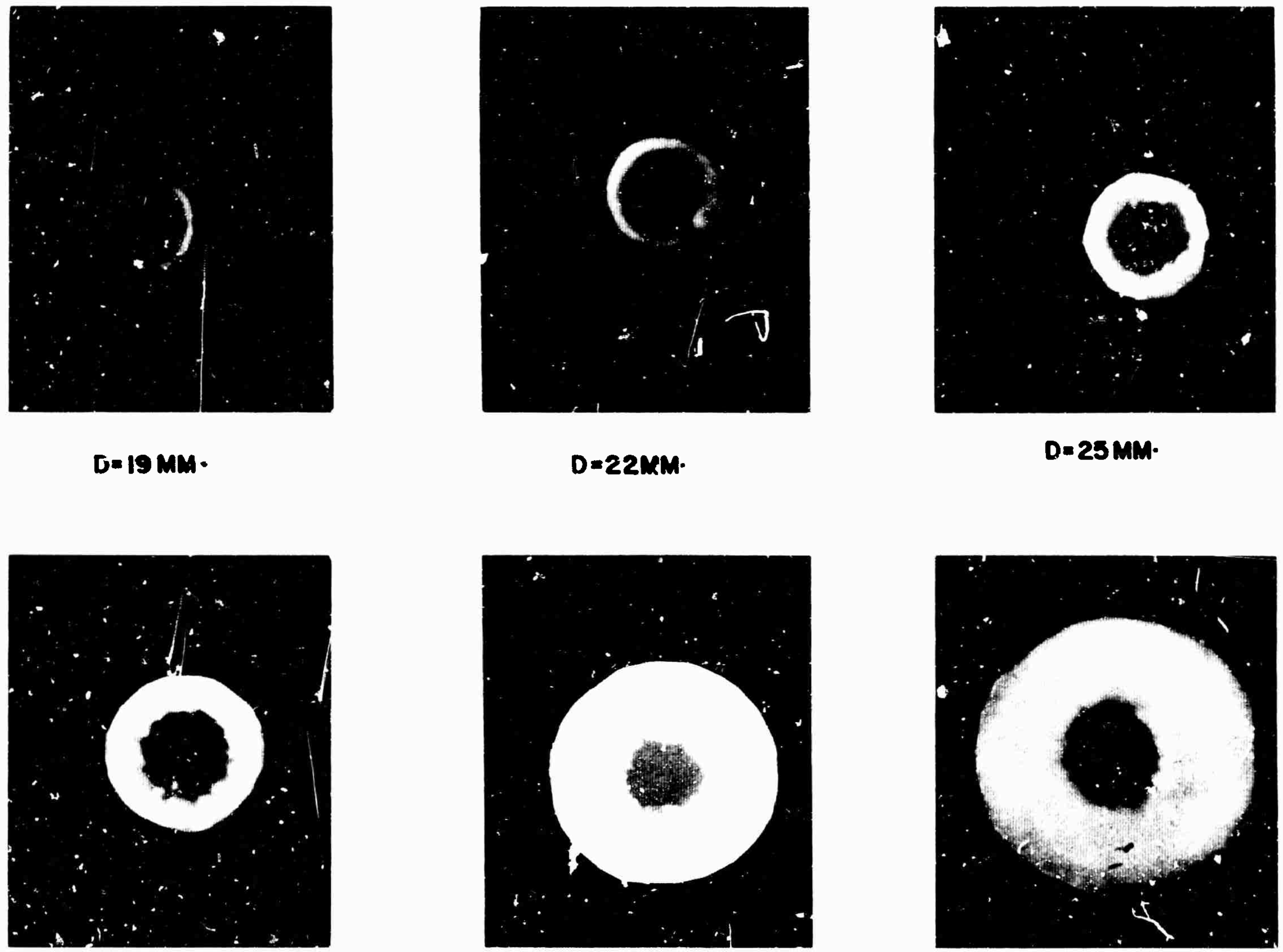
FIG. 2-2 PEAK AMPLITUDE OF P-WAVES AS A FUNCTION OF CAVITY DIAMETER

glas than in aluminum, and in each case that radius corresponds to the smallest cavity used for which no macroscopic inelastic behavior (crushing and cracking) was observed. The cavities for which the amplitude increased with radius apparently responded elastically, and the pressure on the wall did not decrease fast enough to offset the increase in amplitude with cavity size for constant input pressure predicted by theory. The same result was obtained by plotting the peak amplitude from the spectrum of the wave rather than the peak from the seismogram.

The amplitude data for cavities in Styrofoam were more erratic, but again a well-defined minimum was observed when the cavity was just big enough to prevent inelastic failure.

<u>Styrofoam Discs in Plexiglas</u>. The appearance of the shot holes after the detonation is shown in Figure 2-3. When a disc only 16 mm in diameter was used, the Styrofoam was completely removed by the blast, leaving the circular hole in the Plexiglas. At 19 mm, a small fragment of Styrofoam is left. The size of the explosion cavity is constant, and about equal to the 19 mm diameter of the smallest disc shown.

The set of records of the radial component of motion is shown in Figure 2-4. The sequence starts with a shot in pure Plexiglas, goes through increasing disc diameters, and ends with a shot in pure Styrofoam. For all the disc shows the records were made at a distance of 30 cm from the center of the disc. The Plexiglas record was made at 23 cm,



FIG·2-3 THE SHOT HOLES AFTER DETONATION
STYROFOAM DISCS IN PLEXIGLAS

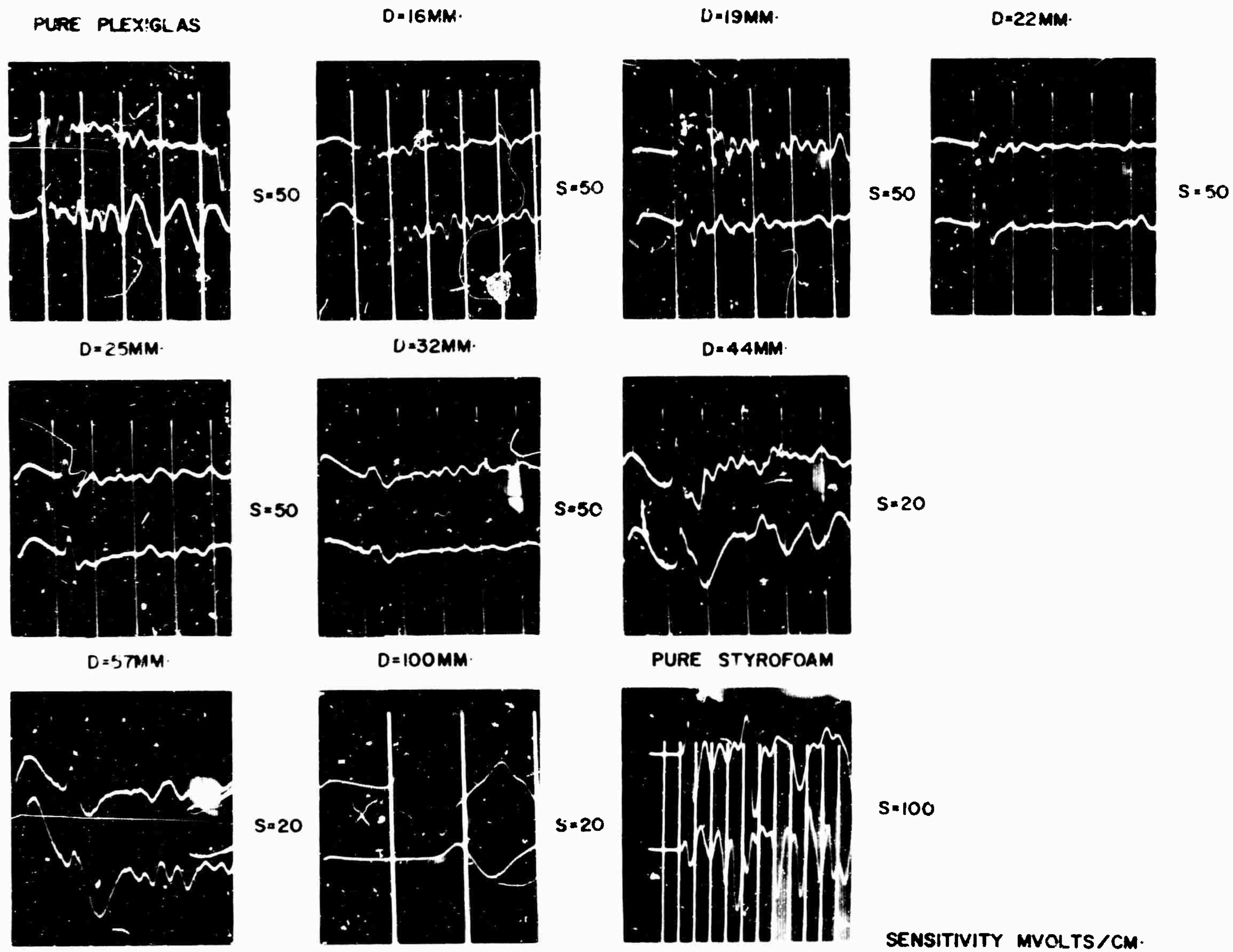


FIG 2-4 RADIAL COMPONENTS OF MOTION STYROFOAM DISC EXPERIMENTS

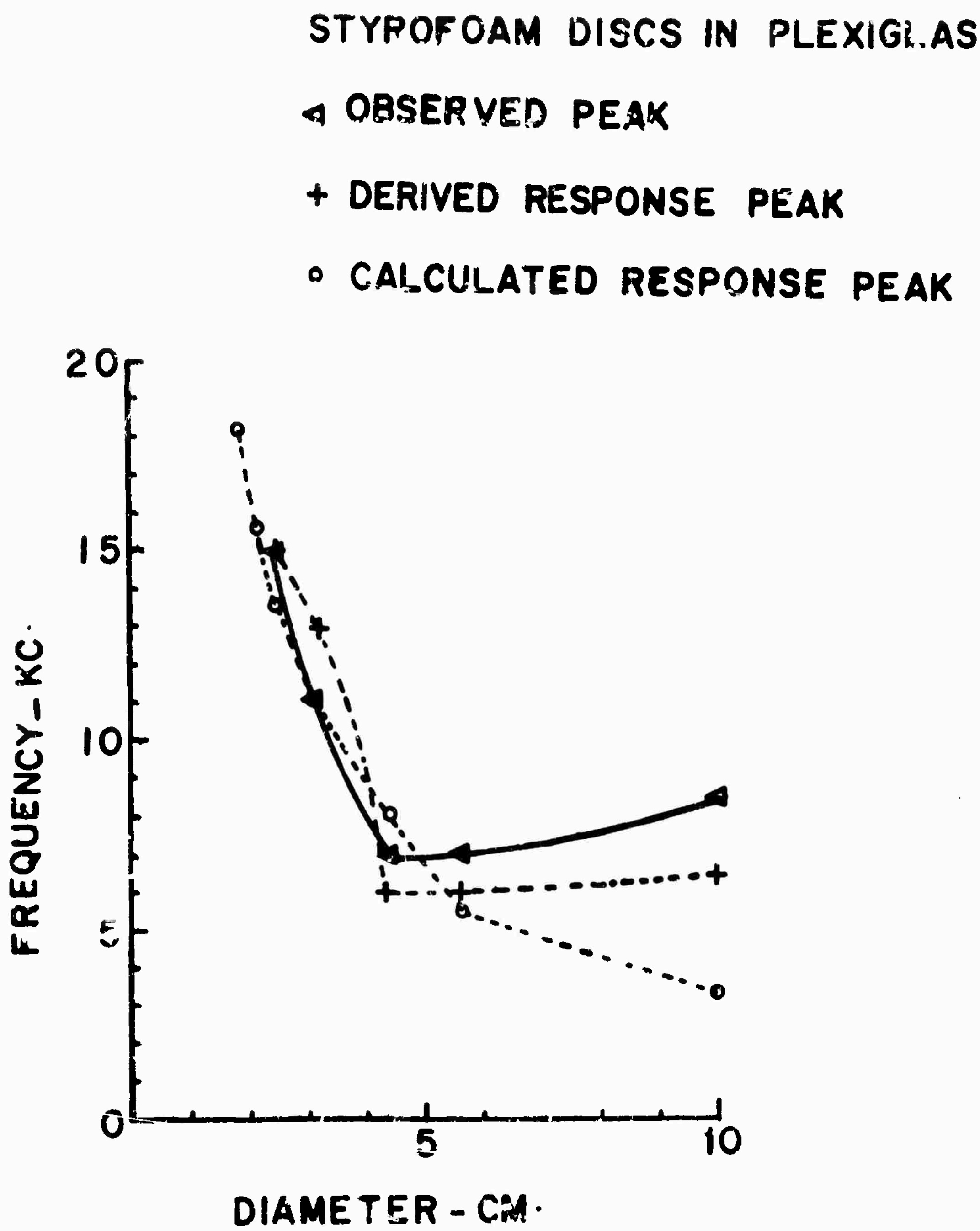
and the Styrofoam record at 20 cm. The timing line interval is 100 microseconds for all records.

The record for the 15 mm disc is hardly changed from that in pure Plexiglas. Then, as the disc diameter increases, the waveform changes progressively to that in pure Styrofoam. The sweep speeds on the last two records are different from the others.

The results for all the diameters for Styrofoam discs in Plexiglas are summarized in Figure 2-5. The variations of he observed peak frequency, the peak of the derived response function and of the theoretical response function with diameter are presented. For all except the largest diameter, the agreement is not bad. For this largest disc, so little energy is present in the neighborhood of the response peak that the method fails completely. In other words, for the largest disc, the effect of the geometry could not be detected, but the effect of the disc material completely determines the observed wave form.

<u>Plexiglas Discs in Aluminum</u>. The data for Plexiglas discs in an aluminum sheet were treated in a similar manner. The results were in good agreement with the predicted peak of the response function, but it cannot be considered as very reliable because of the very low energy in the input spectrum above 50 kcps.

<u>Conclusion</u>. The P wave spectrum can be significantly altered by surrounding the source with a material with properties different from that of the principal medium in



FIG·2-5 SPECTRAL PEAK FREQUENCIES AS FUNCTION OF CAVITY DIAMETER

which the motion is recorded. Even for small cavities, the inhomogeneity is effective, as long as the cavity is big enough that not all of the material in it is involved in the non-elastic region around the explosion. The geometric effects of radiation from a cavity are superimposed, but are effective only over a narrow range of cavity diameters for which the resonance associated with the cavity happens to fall near the peak of the input spectrum, as determined by the response of the cavity material to the explosion.

Rayleigh Waves in a Half-Space.

The model technique was employed to investigate one of the fundamental questions concerning an explosive seismic source: At what depth does the effect of the explosion change from a surface source to a buried source? It was decided to approach this problem by analysis of the non-dispersed Rayleigh wave generated in a half-space by an explosion near the surface because the theoretical results of Lamb (1904) for a surface source and Lapwood (1949) for a buried source were available.

The details of the study are presented in Gupta and Kisslinger (1964a) and Gupta (1964). Samples of the records are presented in those publications. Observations were obtained in all three model materials for shots fired on the free surface and at depths in the interior up to 2 cm.

The records for surface shots in Plexiglas and aluminum agree closely with the theoretical waveforms predicted

by Lamb, while those in Styrofoam do not. The explanation offered is that shots on the surface of the former two materials do not break the surface and are effectively vertically applied pressure pulses of the kind assumed by Lamb. On the other hand, a surface shot on Styrofoam creates a large semi-circular crater, and the loading is obviously not equivalent to the simple vertical pulse.

The Rayleigh waves generated by a buried explosion are approximated by Lapwood's waveforms if an impulse is assumed as the input waveform for Plexiglas and Styrofoam and a step function for aluminum. This difference in the response is due to the differences in the compressional wave speeds in the materials. The same loading will look like an impulse to a slow speed material and a step function, or at least a slowly decaying function, to a high speed medium.

The theory predicts a reversal of polarity on both the radial and vertical components between a surface and a buried shot. This reversal is clearly seen on the records. By increasing the depth in small increments, it was possible to determine the approximate depth at which the effect of the explosion changed from a surface source to a buried source. The results were 4 mm in Plexiglas and 1 mm in alumirum. These are the same as the previously observed radii of the non-elastically deformed zones in the two media. It appears that the critical depth is equal to the radius of the zone of crushing and cracking

When the non-elastic zone intersects the surface, the shot behaves as a surface source; when it does not, the shot is a buried source.

It should be emphasized that the reversal of polarity occurs on both components, so that the motion is still retrograde elliptic. In a separate series of experiments, the reversal with depth of the observing point of the radial component only, which changes the motion from retrograde to prograde, was observed.

This change in the effect of the explosion for a small change in source depth should be tested for the data from full-scale explosions. In those experiments the effects of dispersion will have to be removed by phase equalization.

CHAPTER III

Seismic Effects of Explosions in a Prestressed Medium

Introduction

The extent to which the tectonic strain field in a material affects the seismic wave generated by an explosion in that medium is not known. The conclusion of an early calculation by Press and Archambeau was that while some of the strain energy in the rock will be released when an explosion is detonated, the contribution to the seismograms of the resulting ground motion is smaller than the seismic energy propagating directly from the explosion by a couple of orders of magnitude.

In spite of this conclusion, the suggestion has been made repeatedly that a pre-existing strain field will significantly modify the seismic waves. Departures from symmetry of seismic radiation and the prominent S-wave generated by some explosions, especially in strong rocks, have been offered in support of this hypothesis.

There are two different ways in which the existence of appreciable strain in the medium before the explosion might affect the seismic signal. When a cavity is formed by the explosion, there must be a redistribution of strain in the immediate neighborhood of the cavity, in order to accommodate the new stress-free boundary. This redistribution must occur quickly, and the disturbance created

will propagate outward as an elastic wave. The energy is derived from the static strain field.

In addition, if the strain field is other than purely hydrostatic, as we would expect in a tectonically active area, certain directions will exist in which the material will rupture more easily to form tensile and/or shear cracks. Crack formation resulting from the passage of the explosion-generated shock wave will be guided by the strain field, producing cracks as sources of seismic waves, and the production of cracks in preferred directions will create a pattern of non-symmetric radiation, with significant shear waves. The energy in these waves is derived from both the explosion energy and the pre-existing strain field.

In order to gain more insight into the phenomena described above, a series of model experiments were carried out. Sheets of Plexiglas were stressed in uniaxial tension, and the waves generated by explosions at different stress levels were observed. In a number of the experiments, the capacitance pickups used in all earlier work were replaced by SR-4 strain gages designed for dynamic strain measurements. We have not developed a satisfactory method for calibrating the capacitance pickups for absolute displacement. Since quantitative measures of seismic energy were required, the strain gages were used. A single gage can be used only for P-wave measurements, but combinations of gages can provide shear wave data.

Anisotropy Produced by Static Stress.

In order to detect the effect of static strain on the velocity, a sheet of Plexiglas (1/8" X 26" X 30" length) was stressed under an uniaxial tensile load ranging up to 6,000 lbs.

Figure 3-1 shows the seismograms obtained, under various tensile loads, by using piezoelectric transducers as the source and receivers. The two receivers were positioned orthogonally with respect to the direction of applied tensile stress at a fixed distance of 24.9 cm from the source transducer.

In each record, the first and second traces correspond to waves travelling from the source in the direction parallel and perpendicular to that of tensile loading, respectively, and the third and fourth traces correspond to the first and second, respectively, with the time scale magnified five-fold.

No detectable change in velocity in the transverse direction was observed from the records. For the purpose of computing the anisotropy factor, defined as the ratio of velocity in the transverse direction to that in the longitudinal direction, a constant value of transverse velocity corresponding to that at no load was used. Because the total travel-time of the P wave from the source is much greater than the difference in travel times in the two orthogonal directions, any small and undetected variation in velocity in the transverse direction will have

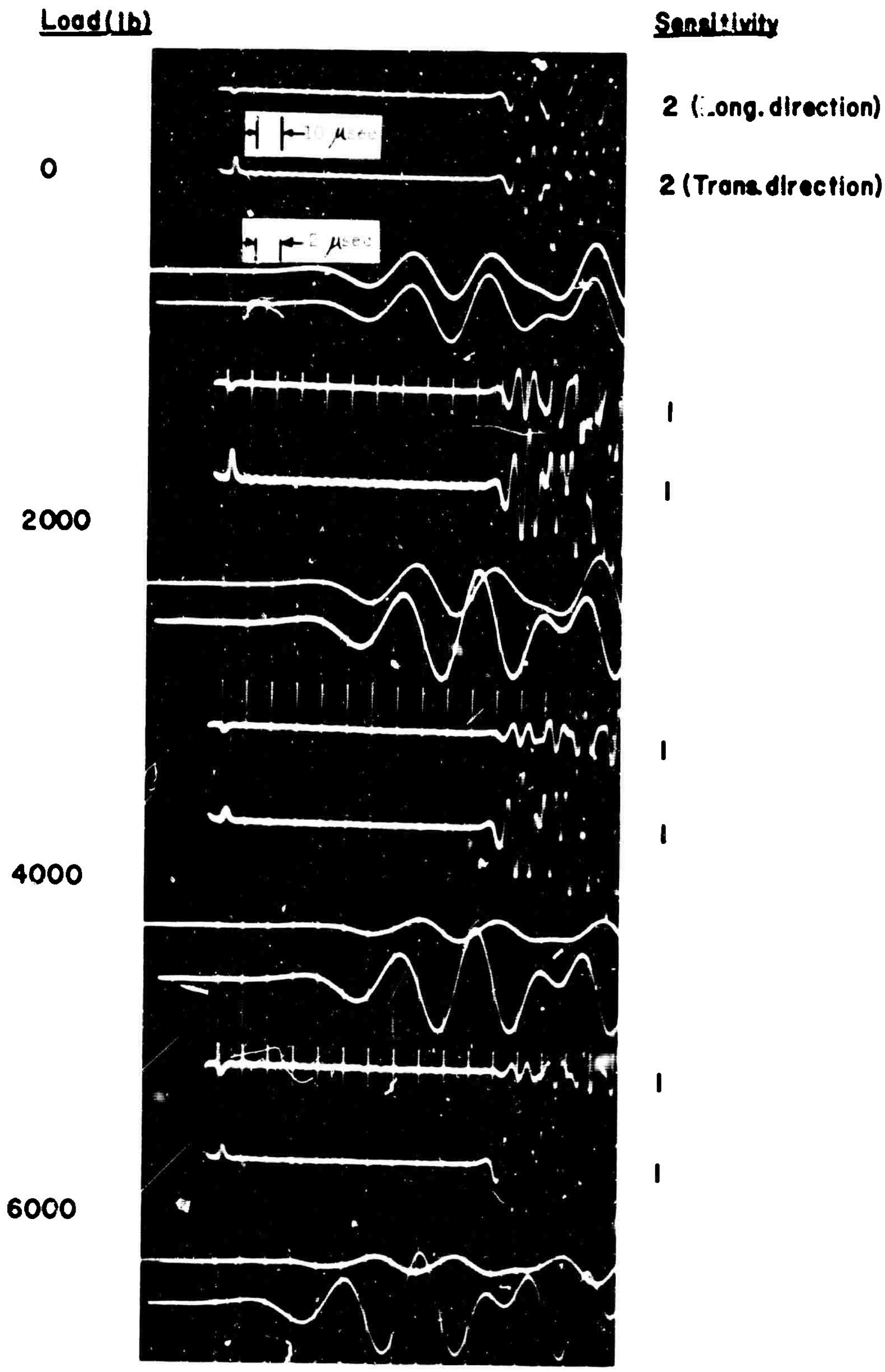


FIGURE 3-1
SEISMOGRAMS OBTAINED UNDER VARIOUS TENSILE LOADS

negligible effect on the anisotropy factor computed.

The experimentally obtained relationship between the anisotropy factor and applied tensile stress is shown graphically in Figure 3-2. It is seen that the anisotropy factor increases gradually with increasing tensile load and reaches about 1.015 at the tensile stress of 1,800 psi.

Since the experiment conducted in prestressed Plexiglas sheets, described in the following section of this report, was primarily carried out in the range of applied tensile stress less than 1,000 psi, the difference of P wave velocity in the orthogonal directions is expected to be less than 1% in view of the relation shown in Figure 3-2.

Therefore, it can be stated that so far as travel-time of the elastic waves is concerned, the effect of anisotropy produced in Plexiglas by prestressing in the working range (say, up to 2,000 psi) while readily observable, can be considered negligible.

<u>Failure Mechanism of Plexiglas in Tension.</u>

When a brittle material like Plexiglas fails under tensile loading, the failure process is essentially a tearing apart without prior permanent plastic deformation (Rinehart and Pearson, 1954). Once failure is initiated at one or more points, brittle fracture will tend to propagate in the direction normal to the applied tensile stress. The fracture will continue to propagate in that direction until the local stress concentration which has been built up at the tips of the advancing cracks falls below the

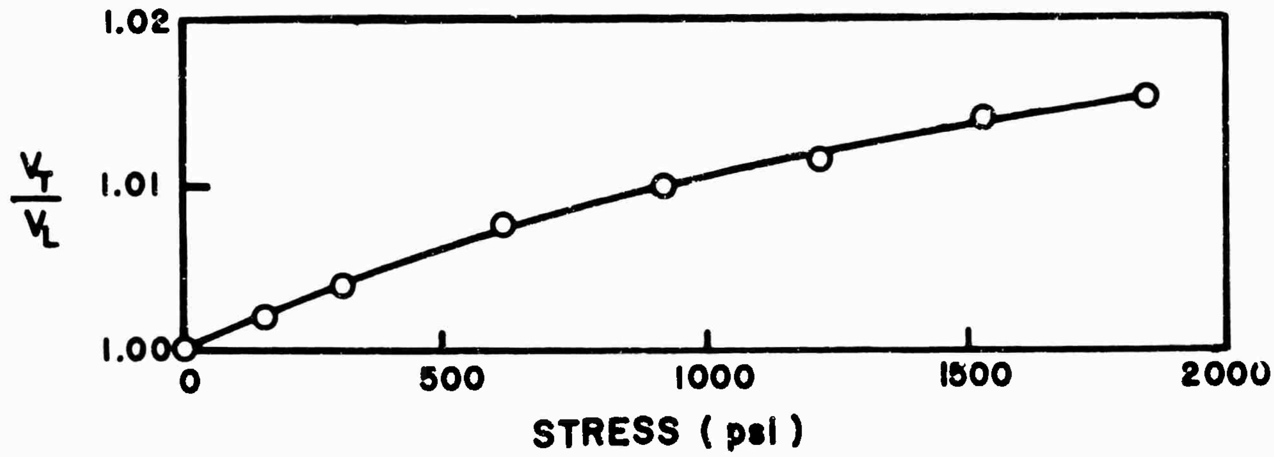


FIG. 3-2 ANISOTROPY FACTOR vs TENSILE STRESS

limiting value for fracture.

The energy needed to initiate and to propagate a brittle fracture is small compared to that in a ductile material. The only work required to initiate cracks in Plexiglas is the work to overcome the molecular bonding force of the specimen.

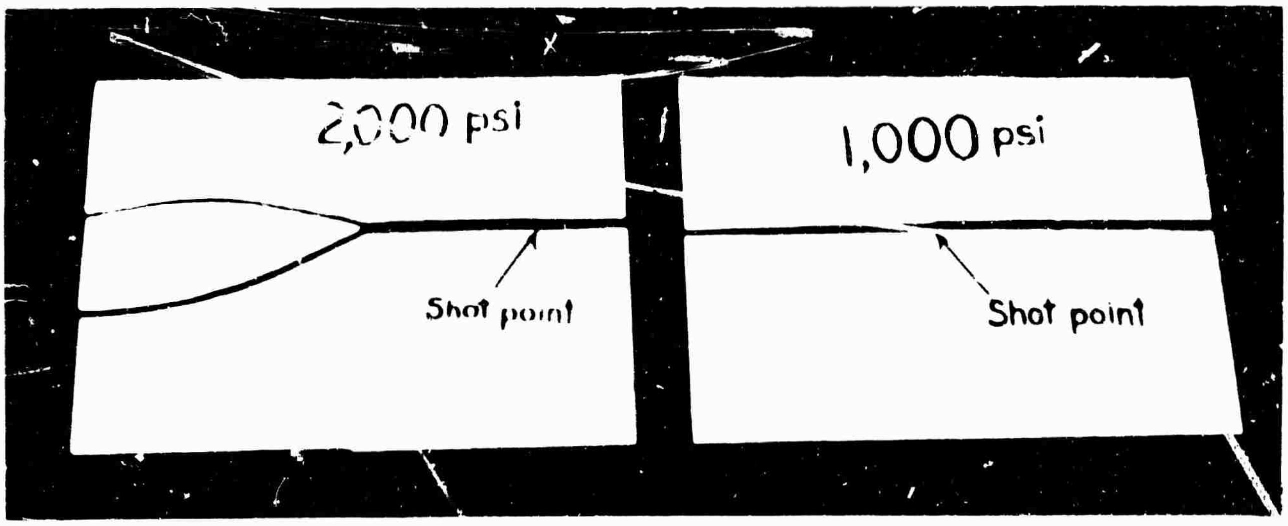
Figure 3-3 shows the patterns of complete crack failure produced by explosions in Plexiglas under tensile stress of 1,000 and 2,000 psi, respectively.

Crack failure of Plexiglas under tensile stress of 2,000 psi apparently occurred simultaneously with the detonation of the explosive in the shot hole. The branching or forking pattern shown in Figure 3-3a should be noted.

However, under the applied tensile stress of 1,000 psi, the crack failure occurred a few seconds after the explosion. This time delay might have been necessary to permit some plastic deformation at the tips of the fractures around the shot, so that the stress concentration at these points increased just enough to overcome the tensile strength of the specimen and to initiate the crack propagation in a straight line in the direction perpendicular to the applied tensile stress as shown in Figure 3-3b.

Difference in the phenomenology of the crack propagation is mainly governed by the level of the applied stress which in turn affects the rate of the crack propagation.

According to Yoffe (1951), who investigated "the moving Griffith cracks" with finite velocity, there is a



(a) (b)

FIG.3-3 EXPLOSION-INDUCED RUPTURES IN PRESTRESSED PLEXIGLAS SHEETS

critical velocity, about 0.6 times shear velocity of the material, at which the crack tends to become curved. This curving is a result of the almost uniform distribution of stress along wide circular arcs ahead of the crack tips.

For the case of the velocity lower than the critical value, however, there exists a high stress concentration in the direction perpendicular to the applied stress.

We have not attempted to measure the velocity of the crack propagation.

An increase of applied tensile stress increases the stored strain energy in a plate. Once crack propagation is initiated, a greater amount of strain energy release would occur at the higher stress level than at the lower stress level, thus producing a greater rate of crack propagation (Schardin, 1959).

The effect of difference in the initial strain energy in the medium is exhibited in the two modes of cracks shown in Figure 3-3, namely, branching crack due to uniform stress distribution, and straight crack due to a high stress concentration ahead of the moving crack tips.

Surface Energy Density.

In the field of fracture mechanics, the Griffith theory of brittle strength has been extensively applied to explain fracture mechanisms in brittle materials (Griffith, 1920; Bueche and Berry, 1954).

If a (tensile) crack is initiated and propagated, the amount of strain energy stored in the prestressed material

will decrease. If the original strain energy is at least equal to the energy required to produce a new surface, the existing length of crack will increase and the specimen will then rupture.

The Griffith equation for the plane stress is:

$$\sigma = \sqrt{\frac{2ET}{\pi c}}$$

or

$$T = \frac{\pi c \sigma^2}{2E}$$

where σ = tensile stress

E = Young's modulus

c = half length of the crack

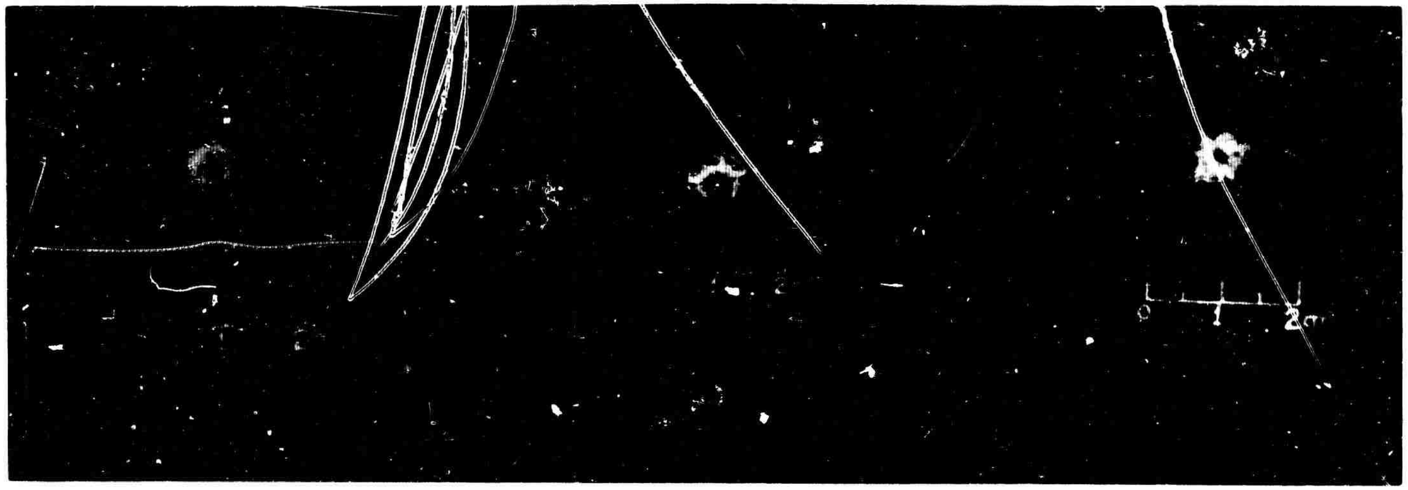
T = surface energy density of a specimen.

Since well developed cracks in the direction normal to the applied tensile stress for the case shown in Figure 3-3b were observed during the few minutes before rupture it is not unreasonable to take the length of the crack before the rupture to be the crack length; i.e. 2c in the Griffith equation.

The value of the surface energy density, T, of 3 mm thick Plexiglas, determined from static strain measurements, was found to be 1.45×10^5 erg/cm^2, which is fairly close to the observed value of 2×10^5 erg/cm^2 (Rosen,1964).

Fracture patterns produced around the shot point under various applied stresses are shown in Figure 3-4.

Under no applied stress, more or less uniform fractures



applied
tensile stress   0 psi   667 psi   1,000 psi

FIG.3-4 EXPLOSION INDUCED FRACTURES IN PLEXIGLAS

are formed around the shot point; however, as the tensile load increases, the fracture patterns show a definite tendency to form strong cracks in the direction nearly normal to the applied tensile stress. This directional cracking is controlled by the release of the stored strain energy in the prestressed medium and is (partially) responsible for producing the asymmetrical radiation patterns of the elastic waves as will be seen later.

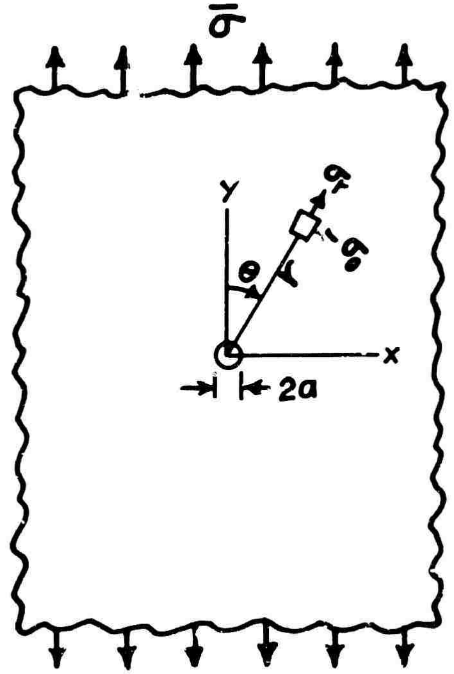
Equivalent Fractured Radius.

When a circular hole is introduced in the plate that is subjected to a unidirectional tensile load, the stress distribution no longer remains uniform around the hole.

The expressions for stress distribution of a thin plate of infinite width with a circular hole under tensile load can be obtained by solving the biharmonic stress function with proper boundary conditions and is given by Muskhelishvili (1963). These expressions are shown in Figure 3-5.

In order to detect the change in the stress field before and after an explosion in the prestressed Plexiglas, two SR-4 strain gages were cemented at distances of 7 mm and 15 mm from the center of the hole, respectively. To minimize the effect of averaging in detecting strain around the gage position, a short gage length was used.

As the tensile load was applied to the Plexiglas sheet gradually up to 667 psi, the values of the tensile strain read from both gages remained the same under the same load,



$$\sigma_r = \frac{\bar{\sigma}}{2}\left(1-\frac{a^2}{r^2}\right) + \frac{\bar{\sigma}}{2}\left(1-\frac{4a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta$$

$$\sigma_\theta = \frac{\bar{\sigma}}{2}\left(1+\frac{a^2}{r^2}\right) - \frac{\bar{\sigma}}{2}\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta$$

$$\tau_{r\theta} = -\frac{\bar{\sigma}}{2}\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta$$

$$\frac{\sigma'_\theta\big|_{\theta=\frac{\pi}{2}}}{\sigma_\theta\big|_{\theta=\frac{\pi}{2}}} = \frac{1+\dfrac{a_e^2}{2r^2}+\dfrac{3a_e^4}{2r^4}}{1+\dfrac{a^2}{2r^2}+\dfrac{3a^4}{2r^4}}$$

FIG. 3-5 STRESS IN AN INFINITE PLATE WITH A CIRCULAR HOLE UNDER TENSILE LOAD (after Muskhelishvili)

as expected at these distances from the shot hole.

After the tensile load reached the value of 667 psi, the explosion was detonated. Reading made immediately after the explosion from the strain gage at 15 mm from the hole indicated an increment of the static strain of 160 μin/in. Another reading made from the same gage at a subsequent time (about 2 minutes) after the explosion indicated a decrease of 30 μin/in from the previous reading. This decrease may be accounted for by relaxation of the newly developed strain field. No reading could be made from the closer gage as it was damaged due to excessive loading by the transient strain from the explosion.

The region fractured by the explosion can no longer carry the high stress as before. It is observed that the shape of this fracture region is not quite circular, but the over-all shape does not depart very much from this.

If we take the newly developed fractured region to be circular as a first approximation, we can then use the expression for the stress distribution to estimate an equivalent radius at which the normal and tangential stresses vanish. We shall call this the "equivalent fractured radius," a_e.

If we let a_e be equal to some constant, K, times the original hole radius, a, and substitute it into the equation at the bottom, we now have a biquadratic algebraic equation in K.

Solving this equation, we obtained K to be about 11,

thus giving the value of the equivalent fractured radius equal to 7.3 mm. This value is about 11% larger than the apparent observed radius of the fractured region and may be regarded as an upper limit on the equivalent fractured radius.

The letters A, B, and C in figure 3-6 represent the relative stress values at the gage location before, immediately after, and about 2 minutes after the explosion, respectively.

Both curves on the left and right sides essentially have the same stress distribution except that the one on the left side uses the reduced radial distance while the other on the right side uses the radial distance.

Strain Energy.

Strain energy in a transient elastic compressional wave can be computed by integrating the square of the radial strain over the duration of motion and multiplying by a factor which depends on the material property and distance from the shot point (Fogelson, et al, 1959).

The strain energy computed from the strain records gave a fairly constant value of 3.5×10^4 ergs, beyond radial distances of 6 cm from the explosion source. Energy computed from a record at the distance of 1 cm gave a result 6 times as large as the value from the records at the large distances.

We are not certain of the explanation for this, but we believe the record so close to the shot has been influenced

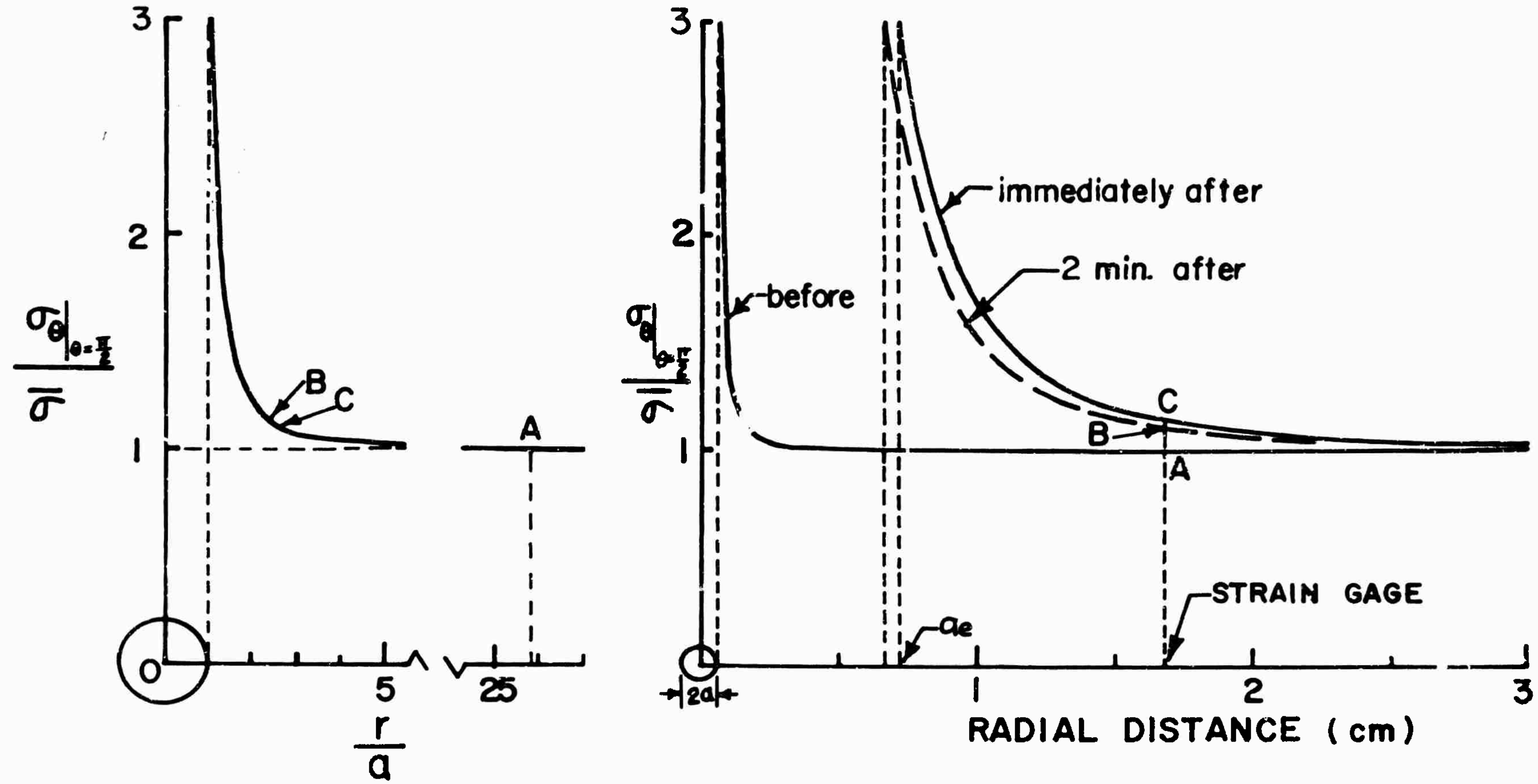


FIG.3-6 STATIC STRESS DISTRIBUTION AROUND THE HOLE BEFORE AND AFTER AN EXPLOSION

by non-elastic behavior, in particular plastic flow. We used the constant value from the larger distances as the energy in the elastic wave.

Using the expression for static strain energy density in a stretched plate, given by Prescott (1961), the static strain energy, under the applied tensile stress of 667 psi, is found to be about 6×10^4 ergs for an area with a radius of 7.3 mm, equal to the equivalent fractured radius.

This calculation was based on the assumption that the significant strain energy release takes place in a volume equal to the volume of the non-elastic zone. This assumption is based on the results by Press and Archambeau (1962) for a spherical cavity in the three dimensional problem. Toksöz, Harkrider, and Ben-Menahem (1965) have presented experimental evidence that a much larger volume must be involved in the tectonic strain release.

Energy in the explosion is calculated on the basis of 400 calories per kilogram to be 2.9×10^5 ergs. Thus, the energy in the seismic wave in the unstressed model is about 12% of the energy in the explosion. This value is very high compared to most experimental results in earth material, especially since much energy is lost into the air.

This calculated strain energy reduction due to introduction of a fractured region around the shot point is about 1.7 times greater than the strain energy in the transient elastic wave generated by an explosion in an unstressed sheet.

Seismograms.

Ideally, an explosive source in an isotropic two dimensional model should be a poor generator of S-waves if the non-linear zone induced from the explosion contains mostly many short radial fractures, uniformly distributed around the hole.

In order to see whether or not the cylindrical charge detonated in a Plexiglas sheet does generate any shear wave, the two capacitance pick-ups were placed at the distance of 15 mm from the shot point with 90° angular separation. Figure 3-7 shows the records obtained with the configuration described above.

However, the sensitivity of the pick-up was made so great in order to detect any small tangential disturbances that the pick-ups recorded a small component of the dilatational wave, as seen in the record. Nevertheless, no significant amount of shear wave disturbances can be seen from the record.

The records of radial strain shown in Figure 3-8 were obtained by using SR-4 strain gages. As the wave length of the elastic waves in our experiment is much larger (at least 40 times) than the gage length, we do not expect any loss in the higher frequency signal content in which we are interested.

Peak strain amplitudes measured from each record were normalized with respect to that of the record #1, in the direction of the applied stress. The radiation pattern

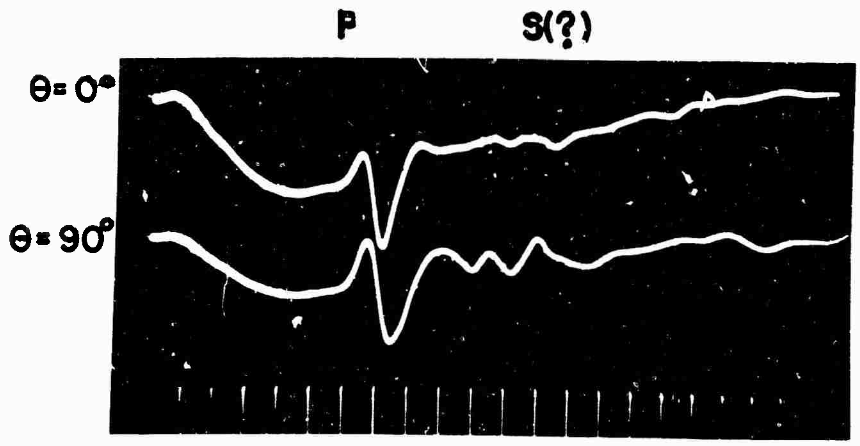


FIG. 3-7 RECORDS OF TANGENTIAL MOTION

(no stress applied)

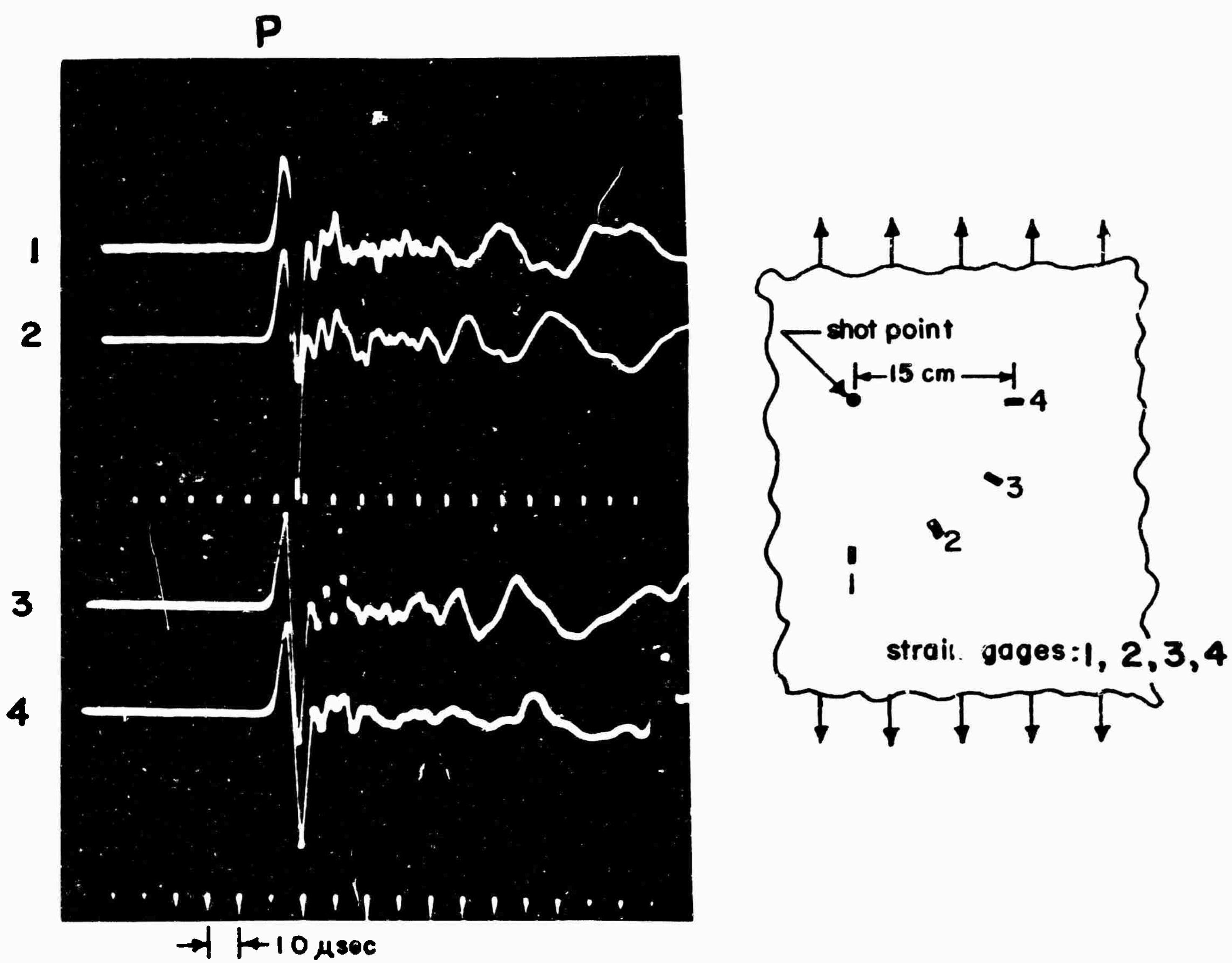


FIG. 3-8 SEISMOGRAMS OF RADIAL STRAINS
APPLIED TENSILE STRESS = 667 psi

from these records will be shown later.

As pointed out by Obert and Duvall (1950) in the case of wave propagation in a three dimensional body (for $r/a >> 1$) the amplitude of the tangential strain is attenuated as the inverse square of the distance, as compared with the inverse first power for the radial strain.

This suggests that the detection of shear waves using strain gages requires a high value of the gage factor and it is desirable to employ two mutually perpendicular gages or a rosette type arrangement.

The SR-4 strain gages used in detecting the P-wave do not have gage factors high enough to permit the detection of small tangential disturbances from the shear wave. However, at a greatly increased cost one could use semi-conductor strain gages that normally have gage factors about 18 times greater than the SR-4 gages.

To detect S motion, four capacitance pick-ups were placed at 15 cm from the shot points with angular separation of 30 degrees covering one full quadrant as shown in Figure 3-9.

Two sets of the records were obtained under the same applied tensile stress of 667 psi, but with difference in the initial shot hole conditions. For the case on the right, the shot hole was intentionally fractured by detonating a charge packed less densely than the normal charge, under no load conditions. This set of records was then obtained by detonating a second charge of normal strength in the

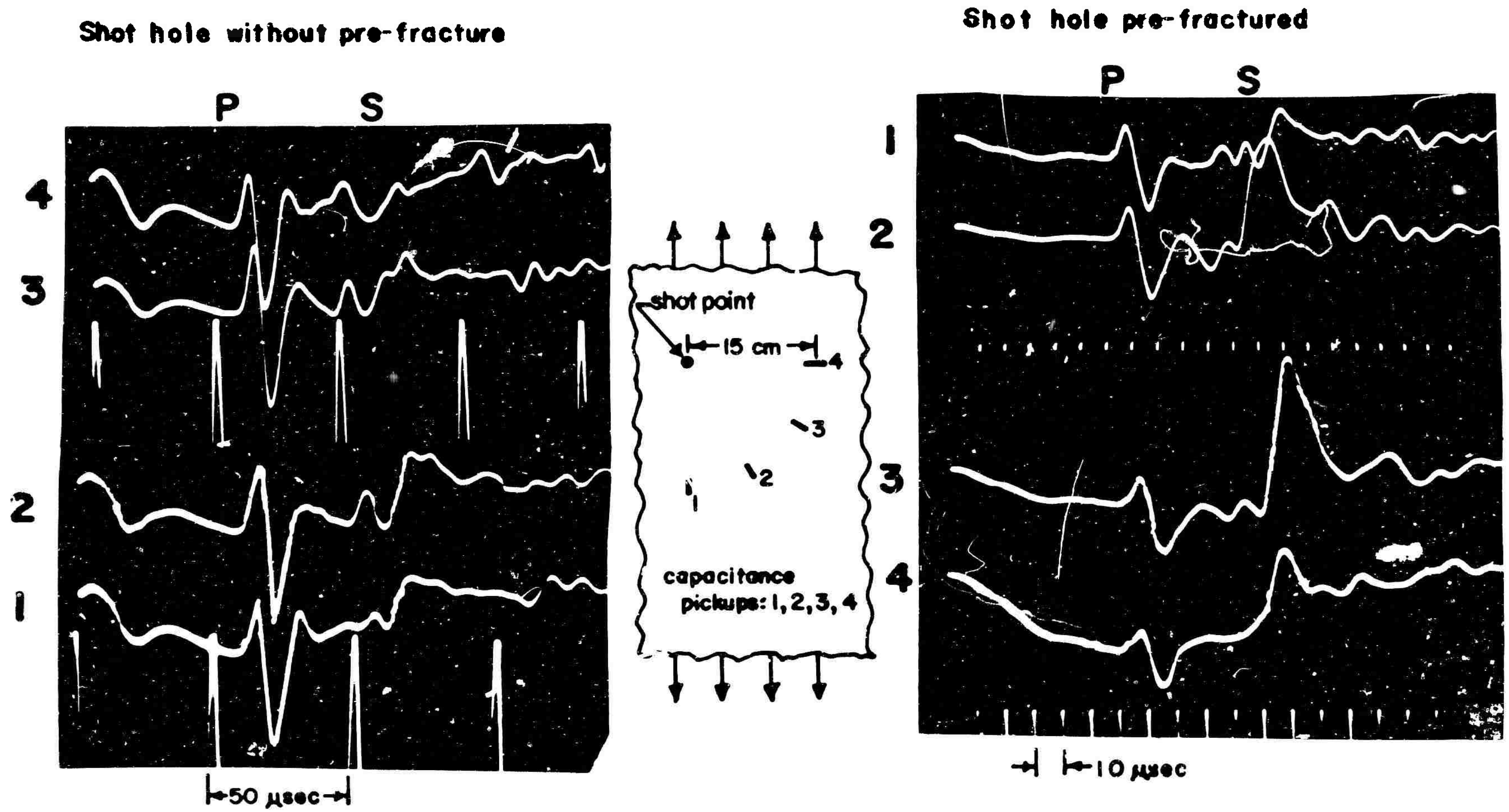


FIG.3-9 RECORDS OF TANGENTIAL MOTION
(Applied tensile stress = 667 psi)

hole surrounded with the uniform fractured zone under tensile stress of 667 psi.

The two sets of records are recorded with the same sensitivity. The relative efficiency of the explosive energy coupling to the medium can be seen by comparing the amplitudes of the P wave in both sets. If there were no pre-fractured zone for the second case, these amplitudes should near about the same, but an amplitude reduction due to introduction of pre-fracture is nearly a factor of two.

The Radiation Patterns.

The observed radiation patterns of P- and S-waves at two different applied tensile stresses are shown in Figure 3-10.

On the far left side, the solid line represents the case of no pre-fracturing of the shot hole, while the dashed line represents the case of the pre-fractured shot hole. Amplitude of the P-wave for the pre-fractured shot hole condition decreased nearly by one-half while amplitude of the shear wave increased nearly by a factor of about 3. The radiation pattern shown in the middle is obtained from the strain records shown in Figure 3-8.

It is seen from the radiation patterns that the difference in amplitudes between the vertical and horizontal directions increases with an increase of the applied stress. (Notice the horizontally shaded region in the P-wave radiation patterns.)

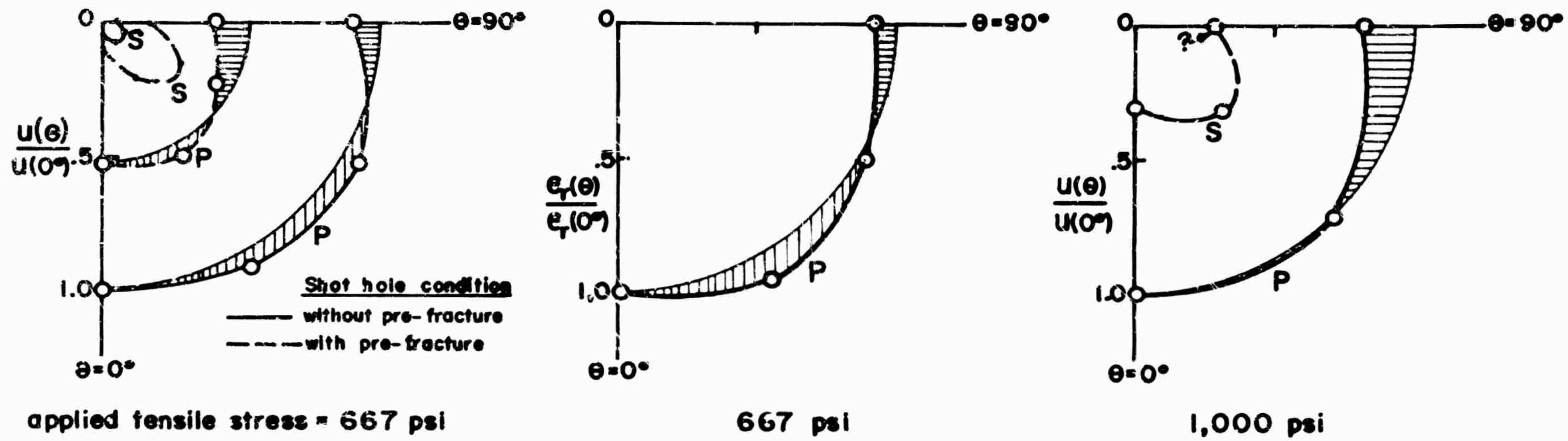


FIG. 3-10 OBSERVED RADIATION PATTERNS OF P- AND S-WAVES

The ratio of maximum amplitude of the shear wave to that of the P-wave at the applied stresses of 667 and 1000 psi are 0.1 and 0.4, respectively.

As we have seen from the record obtained under no applied stress, we would expect the value of the amplitude ratio of the S wave to the P wave to be very small. Thus we may take this value to be equal to the zero. Using these three sets of values, we obtained the curve shown in Figure 3-11.

Although this curve was drawn from few data points, it suggests that the effectiveness of the shear wave generation is enhanced quite strongly with an increase of the applied stress.

Since the generation of the shear waves is mainly governed by the departure from circular symmetry of the source mechanisms, the behavior seems likely to be the result of the release of the stored strain energy in the prestressed specimen. The manner in which this reduction of the energy would occur is in the formation of cracks in preferred directions to minimize the existing local high stress around the shot point. This tendency of preferential cracking will increase with an increase of the stored strain energy, ultimately forming moving cracks until rupture in that direction occurs.

This preferred direction of cracking in our experiment is found to be along the direction nearly normal to the applied stress.

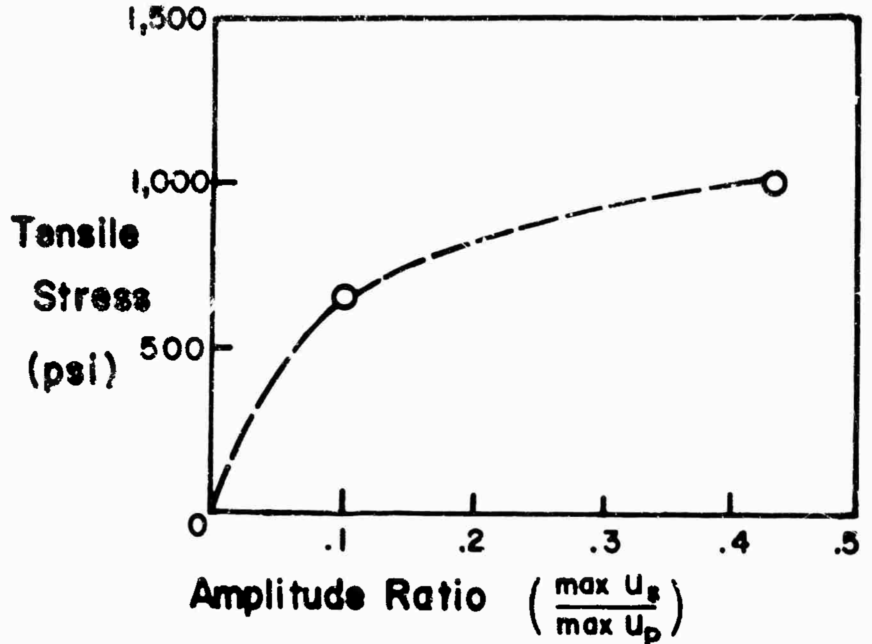


FIG. 3-11 APPLIED TENSILE STRESS VS. RATIO OF MAX. AMPLITUDES OF S- AND P-WAVES

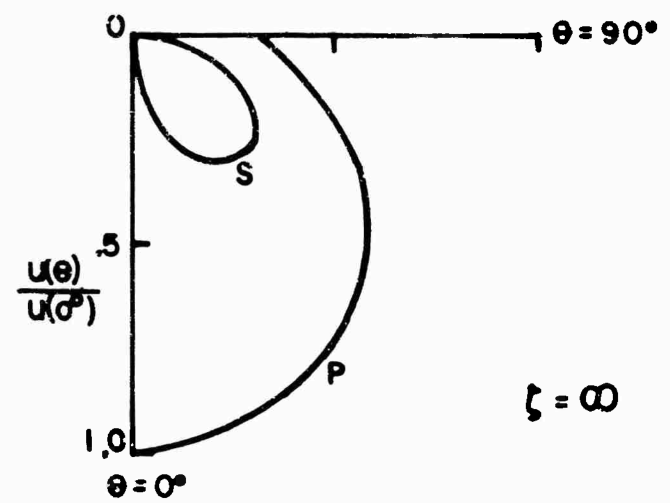


FIG. 3-12 THEORETICAL RADIATION PATTERNS OF FIRST P- AND S-MOTIONS
(After Knopoff and Gilbert, model 3)

Figure 3-12 shows the theoretical radiation pattern of the Knopoff and Gilbert's model 3, "the sudden propagating expansion of a lenticular cavity," the expansion taking place in the direction of the normal to the plane of the cavity walls (Knopoff and Gilbert, 1960).

Comparison of the theoretical radiation pattern with the observed ones reflects a general qualitative agreement.

This theoretical model does not necessarily represent the source mechanism in our experiment. However, it does bring up the significant role that directional cracking caused from the release of the stored strain energy plays in generating the shear waves, with their multipolar radiation pattern.

It should be pointed out that the limitation of the Knopoff and Gilbert model 3 in applying to our two dimensional model experiment is the short length of focal line segments. Although the two-dimensional modeling in plane stress is in fact analogous to a three-dimensional modeling in plane strain, their theory is developed for the case of the short length of focal line segments.

The observed radiation patterns of shear waves show consistently the quadrupolar pattern, the amplitude of which peaks at the angle of about 45° from the direction of the applied stress.

The seismic energy in the dilatational wave is derived from two sources:

(1) one with symmetry from the explosion, and

(2) the other with an asymmetrical distribution from the release of the stored strain energy in the prestressed specimen.

Unfortunately, the separation of one contribution from the other cannot be made quantitatively. However, the relative strength of the asymmetrical source contribution can be observed from the observed radiation patterns, indicated by the shaded region.

Consider an extreme case in which the contribution from the release of the stored strain energy is much greater than the contribution from the explosive. Then, this source would approximately approach a case of the bilateral cracking or tensile fracture. If so, then we should at least be able to compare qualitatively our observed radiation patterns with those of the extreme case.

Conclusions.

(1) Two different modes of observed moving cracks initiated from the explosions in prestressed Plexiglas sheets can be explained from the viewpoint of stress distribution:

a. straight line mode due to high stress concentration ahead of the moving crack tips for the case of lower stress.

b. forking mode due to more or less uniform stress distribution ahead of the moving crack tips for a higher initial stress.

(2) The surface energy density of Plexiglas sheet with a thickness of 3 mm to produce the Griffith crack is found to be 1.45×10^5 erg/cm^2.

(3) The equivalent fracture radius estimated is about 11% greater than the apparent radius of the observed fracture zone.

The magnitude of the strain energy released due to the formation of fractured hole is estimated to be about 1.7 times that of strain energy in the elastic waves in unstressed medium.

(4) The explosion detonated in the pre-fractured hole generated a shear wave much more efficiently, about threefold.

(5) The relative efficiency in generating shear waves in the prestressed Plexiglas increases sharply with an increase of the applied tensile stress.

(6) The multipolar radiation patterns observed are mainly accounted for by the release of the stored strain energy in the form of directional cracks.

It is not surprising to see that, as the Plexiglas sheet used in the present experiment is a brittle material, the fracturing phenomenon played a significant role in the appearance of seismograms obtained.

CHAPTER IV

Propagation in the Neighborhood of a Low-Velocity Wedge

The problem of refraction and diffraction of elastic waves by a low-velocity wedge is important to the seismologist because of the relation of this problem to seismic wave propagation through mountain roots. A model study of this problem has been carried out in which the effect of the wedge on the first arrival was investigated.

An equilateral triangular Plexiglas wedge, 15 centimeters on a side, was embedded in the edge of an aluminum sheet, Figure 4-1. The sources were placed both inside and outside the wedge.

Pulsed ceramic transducers and explosions have been used as sources. To study transmission out of the wedge, a lead zirconate tube was placed at the center. The receiver was placed in the aluminum sheet at different points around the wedge. For transmission across the wedge, the source and receivers were placed in the aluminum on opposite sides of the wedge.

The radial component of motion was measured inside and outside the wedge when the charge was detonated in the aluminum, outside the wedge. The tangential component of motion was measured at some points outside the wedge.

The important properties of the materials have the

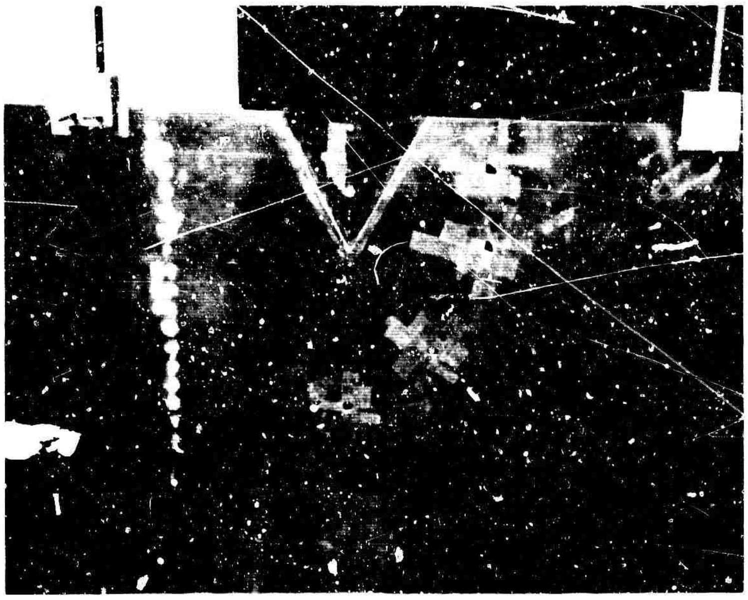


FIG. 4-1 WEDGE MODEL

following values: For aluminum, V_p is 5.4 mm/ μsec; density, 2.8 gm/cm^3; pseudo-Poisson's ratio, 0.26; and mechanical impedance, 15. For Plexiglas the corresponding values are 2.3 mm/ μsec, 1.22 gm/cm^3, 0.25 and 2.8.

Ray paths for P and converted S waves have been constructed using elementary principles. The result for one depth is shown in Figure 4-2. The rays incident at the aluminum-Plexiglas boundary generate reflected and refracted compressional and shear waves. The reflection and the transmission coefficients for a ray at normal incidence (assuming plane wave) are 0.684 and 0.316, respectively.

The critical angle for a ray incident through Plexiglas is about 27°. Most of the rays refracted into the wedge are incident on the Plexiglas-aluminum boundary at angles greater than the critical angle. Hence, most of the rays are totally reflected inside the wedge, and can only leave after one or more additional reflections at the free surface or wedge boundary. There is no direct path for either P or S waves between the source and a receiver across the wedge.

Propagation from Pulsed Transducer Source.

The receivers located outside the wedge in aluminum along a circular arc with the center at the source, and radius equal 25 cm were used to observe propagation out of the wedge. The seismograms and experimental setup are shown in Figure 4-3. The time marks are 100 μsec apart.

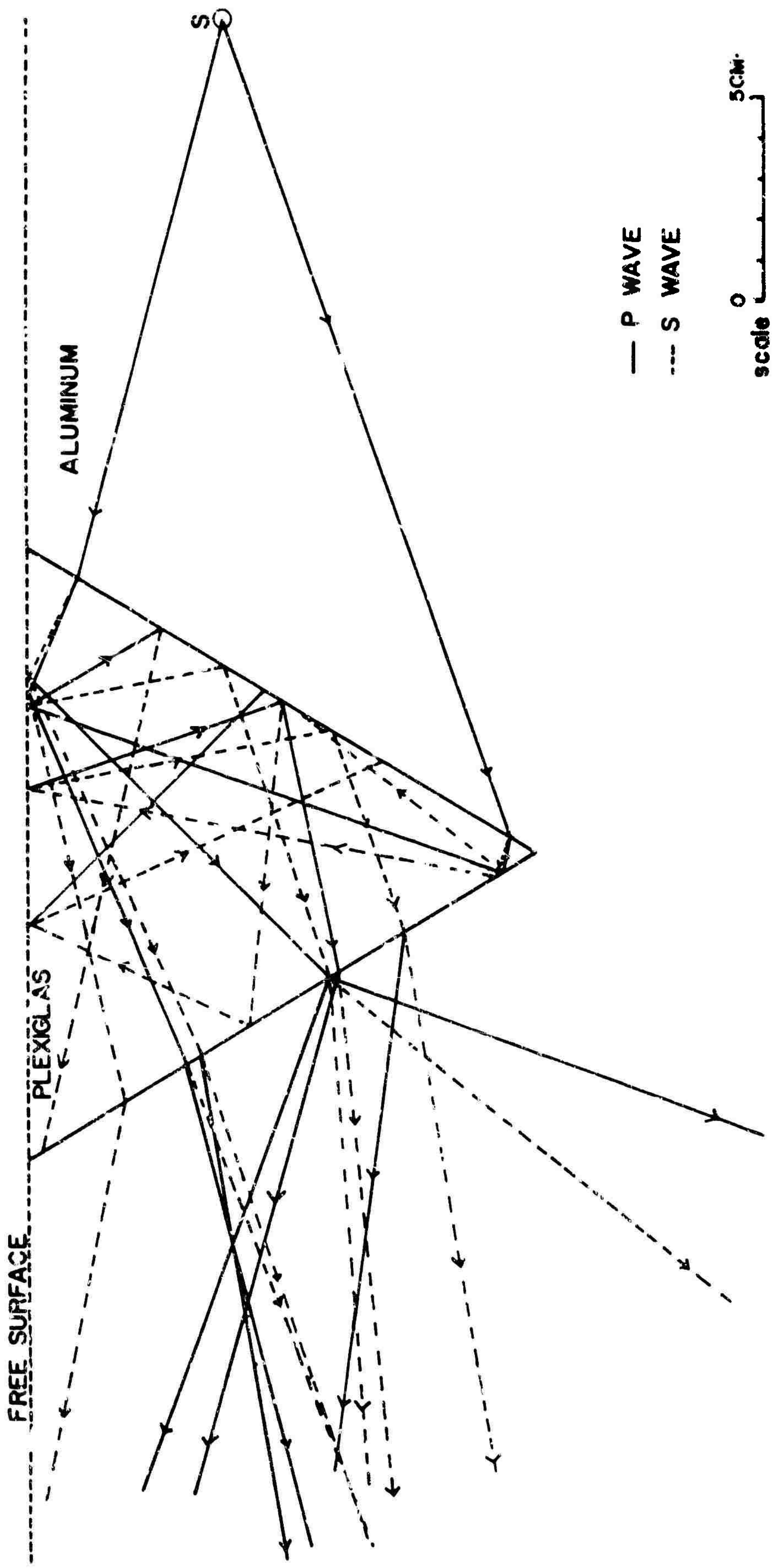
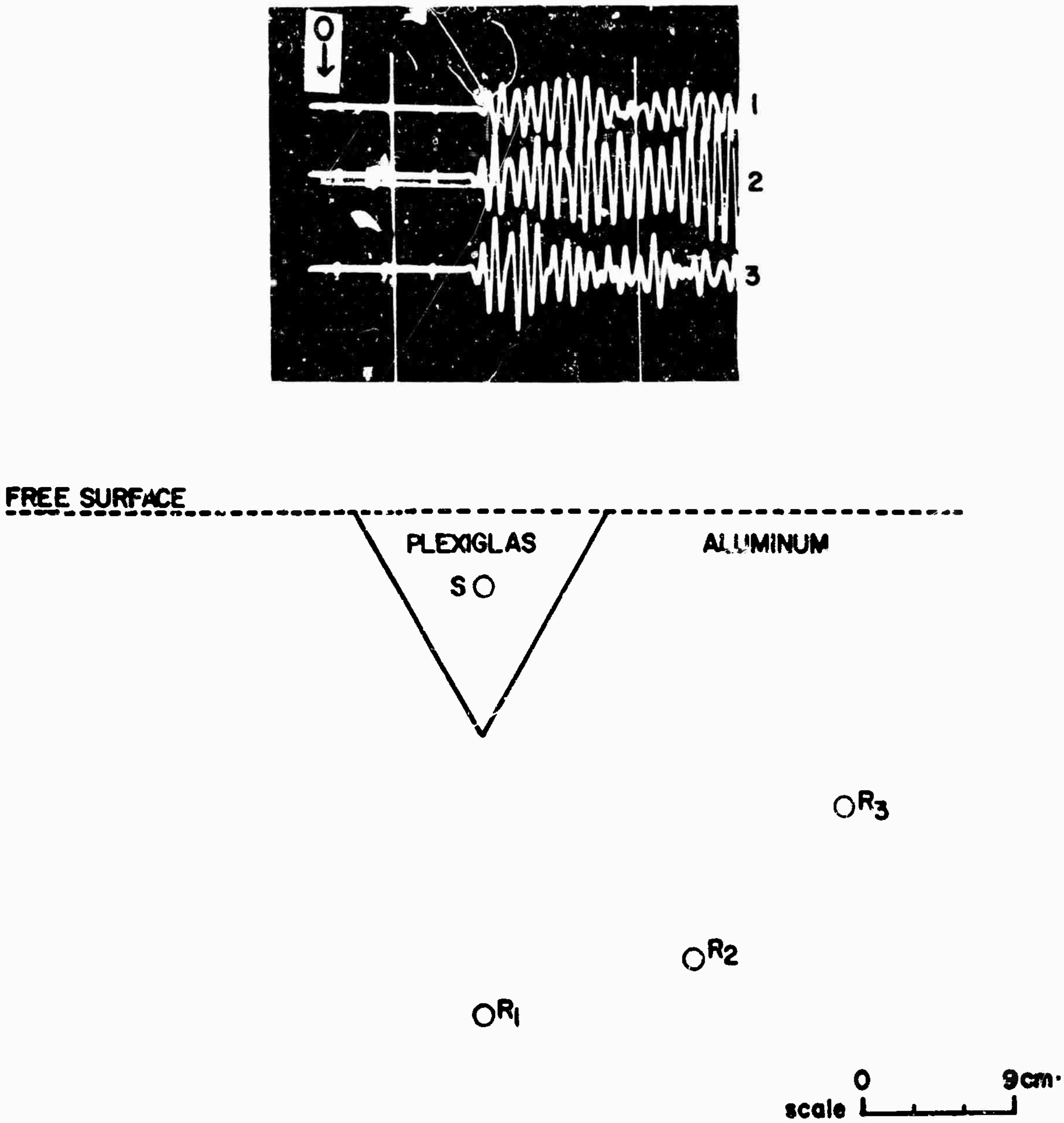


FIG. 4-2 RAY PATH DIAGRAM



FIG· 4-3 PULSED SOURCE INSIDE THE WEDGE

The source has been driven with 2 μsec. pulses.

Comparison with records made with the same source in the aluminum shows that the observed wave form of the initial P motion is hardly affected by the wedge. The wave form is seen to be the same in all three directions.

When the source is outside the wedge, diffracted waves are generated at the tip when incident waves reach there. The diffracted waves appear at time $t = \frac{X_o}{V} + \frac{r}{V}$, where X_o is the distance between the edge and the source, r is the distance between the tip and an observation point, and V is the velocity of P wave in the plate.

Figure 4-4 shows three records from the single detection indicated in the lower part of the figure. The source was driven with a 2 μsec. pulse from a pulse generator. The time scale on the lower trace has been magnified by 2. The time marks are 10 μsec. apart. Source and receiver are 4.5 cm from the edge and 25 cm from the wedge axis. The distance from source to the wedge tip and then to the receiver is 53 cm. The travel time of the first arrival is 100 μsec, in close agreement with the time of a diffraction from the wedge tip. The earliest time an arrival through the wedge could reach the receiver is about 140 μsec, which may correspond to the beginning of the large motion.

The spectra of P from the same source in aluminum and a diffracted P wave are shown in Figure 4-5a. The transfer function has been calculated by dividing the spectrum observed with presence of the wedge by the spectrum in the infinite sheet. The result of division is

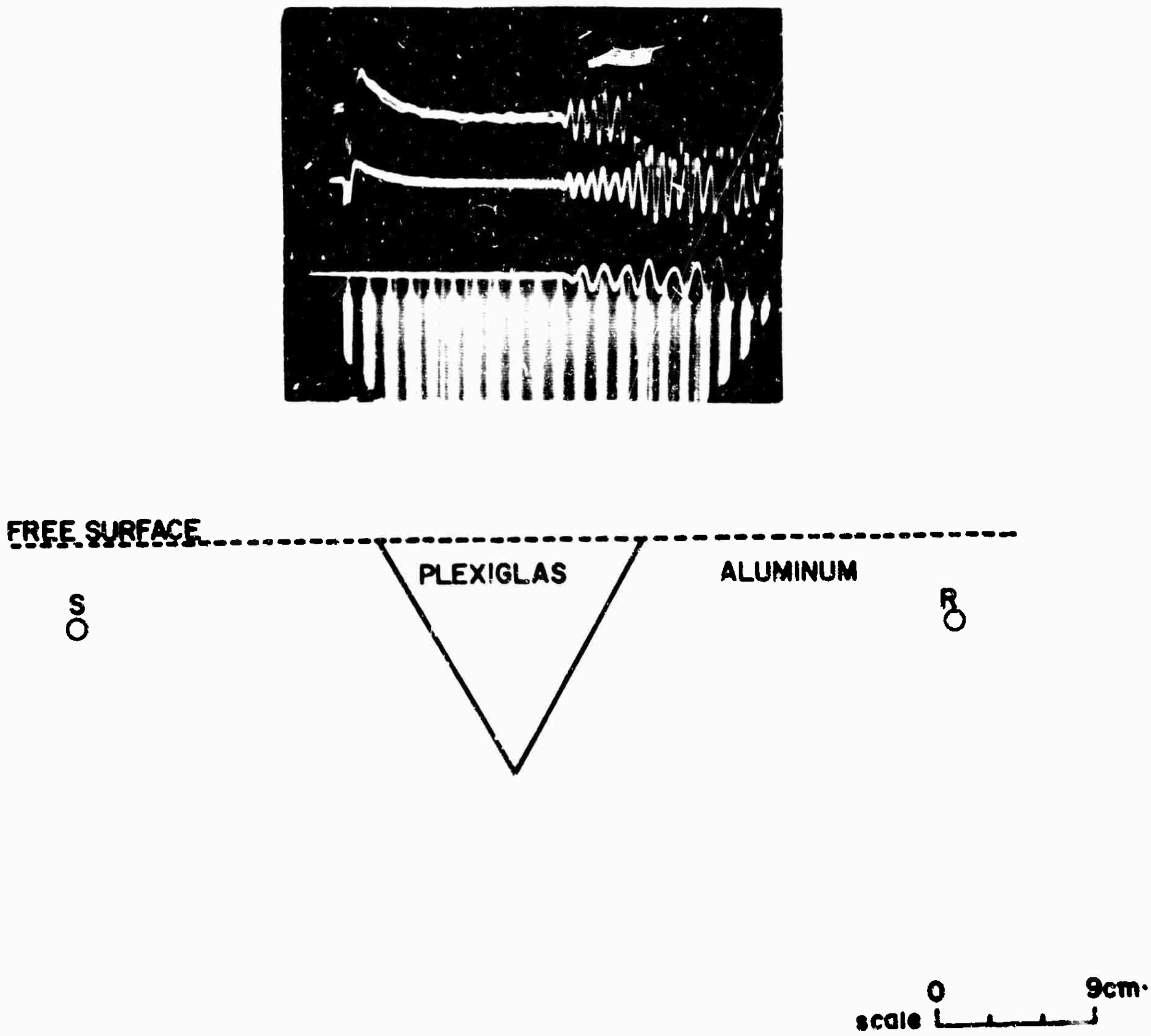
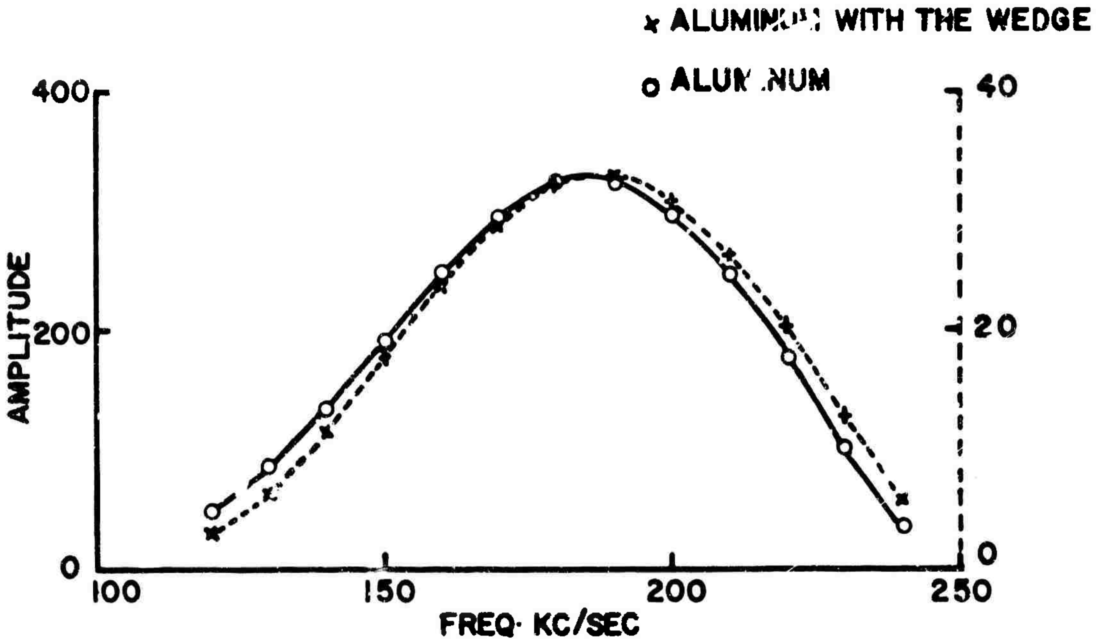
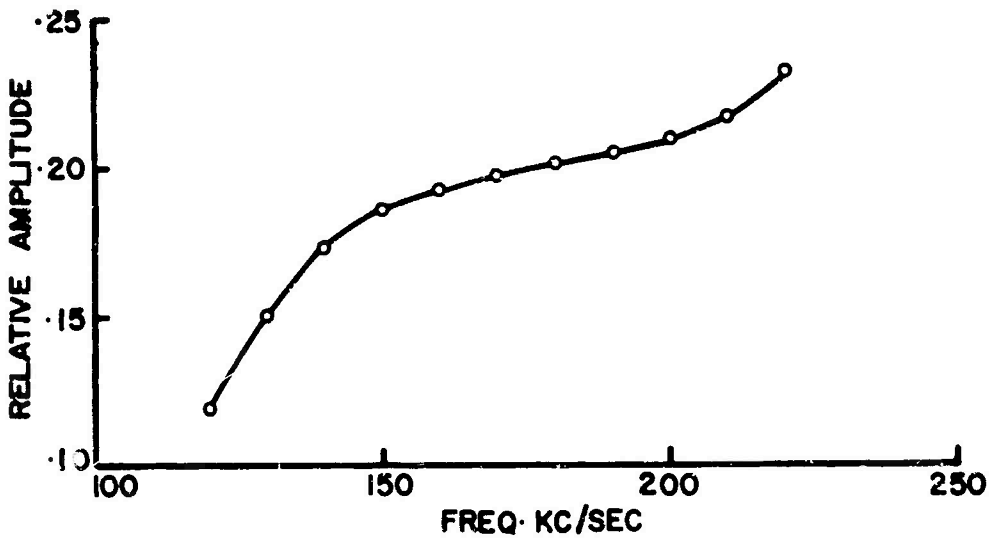


FIG. 4-4 PULSED SOURCE OUTSIDE THE WEDGE



FIG· 4-5a SPECTRA OF INITIAL P WAVE



FIG·4-5b TRANSFER FUNCTION

shown in Figure 4-5b. The transfer function is flat from 150 - 200 kc, which is the range of the frequency of the input signal. This indicates that presence of the wedge has not affected the frequency content of the input pulse.

Propagation from Explosive Source.

For transmission across the wedge, the source and receivers were placed in the model on opposite sides of the wedge and one receiver was placed at the center of the wedge. The experimental setup and sets of record of radial component of motion are shown in Figure 4-6. The amplitude of the first arrival observed along a path which missed the wedge completely, receiver 4, is large compared to the corresponding arrivals behind the wedge, receivers 2 and 3. The wave form in the wedge is the same as outside. Transmission into the wedge is very efficient. The most obvious effect of the wedge is the shadow zone it creates. The large second arrival is a converted wave of some kind, the exact nature of which has not been determined.

The charges were detonated at different depths below the free surface (Figure 4-1), from 2.2 cm to 14.5 cm. As the depth of the source is increased the amplitude of the diffracted wave is increased. The angle of incidence at the wedge tip is decreased with the increase of the source depth. Hence the increase in amplitude is due to the decrease of the angle of incidence at the wedge tip, as the diffracted path approaches the direct path.

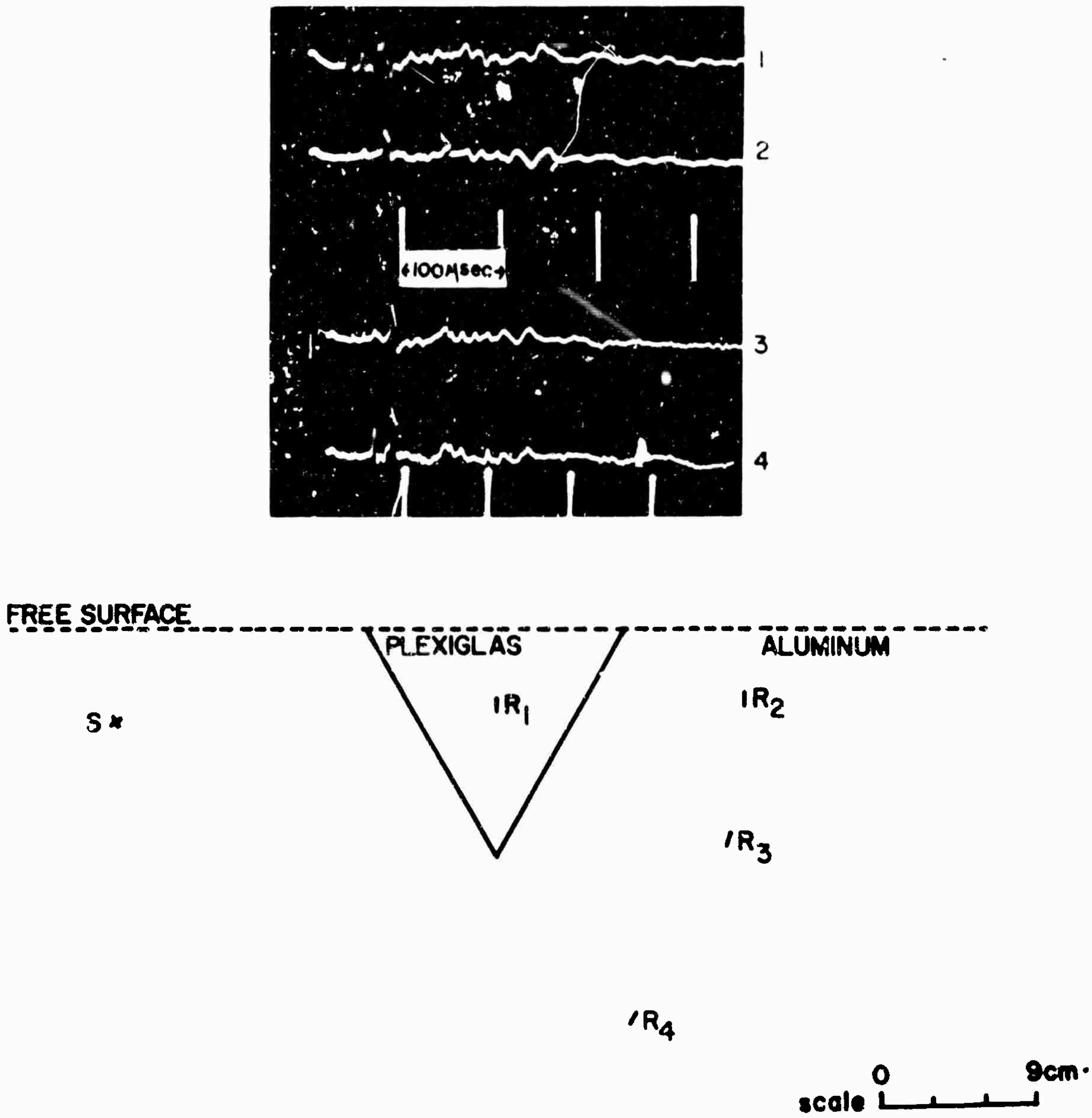


FIG. 4-6 EXPLOSIVE SOURCE OUTSIDE THE WEDGE

Conclusion.

The low velocity wedge makes a distinct shadow zone for waves crossing it. The sharpness of the shadow zone is dependent on the wave length of the traveling wave. Waves with short wave lengths (compared to the dimension of the wedge) will make more distinct shadow zones than longer ones. The travel time of the first arrival in the shadow zone agrees in time with a diffraction from the wedge tip. The amplitude of the diffracted wave is small compared to the direct wave.

The amplitude of the diffracted wave is increased as the depth of the source is increased. The latter is due to the decrease of the angle of incidence on the wedge tip.

The multiply reflected waves inside the wedge will result in complex radiation of later arrivals. This phenomenon is a subject for further study.

Summary and Recommendations

The value of two-dimensional model experiments for investigating the processes by which an explosion in a solid medium generates seismic waves has been demonstrated by the results of the research completed in the present program. The effects of the medium in which the charge is detonated, as well as the effect of the geometry of the source and the environment have been clarified.

With the basic technique developed, many problems can be made the subject of study. Almost any aspect of wave generation that can be studied in full scale experiments can be tested in the laboratory. However, the instrumentation employed in the present work was not completely adequate to permit the full potential of the experiments to be exploited. Two additions to the instrumentation would increase substantially the information from the experiments: a small sensor to measure the wave form and amplitude of the pressure pulse delivered to the medium by the explosion, and equipment for dynamic photoelastic studies, using an ultra-high speed framing camera.

The conclusions reached in the various parts of this research should be subjected to full-scale field testing. These include the effect of source depth, the effect of the shape of the shot cavity, the beaming of energy as a result

of the free surface, and the effect of solid material in decoupling cavities. The first three of these are difficult to test because of the complications introduced by geological variations which will be encountered at any test site.

Further model studies that should be conducted include three-dimensional model studies of decoupling and the use of a material with higher tensile strength, such as aluminum, in the study of the effect of prestressing. Additional experiments directed toward particular problems should be designed as these problems arise.

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Abstract (Cont'd)

When the medium is statically stressed before the shot, the body waves are modified. For relatively small strains in Plexiglas, a definite, but small, anisotropy is produced by the static strain. The presence of the static strain guides the release of energy from the explosion. Complete rupture of the sheet was produced by explosions when the stress was well below the static tensile strength. Small but distinct S-waves were produced in prestressed sheets, but could not be detected in the same material without loading.

A low velocity wedge modifies wave propagation by creating a shadow zone. Diffractions into this shadow zone from the wedge tip were observed.

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13. ABSTRACT

The generation of seismic waves by an explosive source in homogeneous media was investigated by two-dimensional models. The size of the effective source for compressional waves agrees well with the outer limits of the zone of circumferential cracking in a brittle medium. Prominent shear waves appear only when the source produces long radial cracks, is located near the free surface of the model, or the source is elongated. The radiation of both types of body waves is strongly modified when the source is near the surface.

The P-wave spectrum can be modified by surrounding the shot with a different material. A cavity, filled with air or a solid substance, affects the signal through both its geometric configuration and the properties of the material in the cavity.

The evidence from Rayleigh waves indicates that the effect of an explosion changes from a vertically applied source pulse to a buried center of compression when the source depth exceeds the radius of the zone of non-elastic behavior. (Cont'd)

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